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REMEDIAL INVESTIGATION FOR THE QUARRY RESIDUALS OPERABLE UNIT OF THE WELDON SPRING SITE, WELDON SPRING, MISSOURI

VOLUME I

Weldon Spring Site Remedial Action Project
Weldon Spring, Missouri

SUPERSEDED

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U.S. Department of Energy
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Weldon Spring Site Remedial Action Project
Prepared by MK-Ferguson Company and Jacobs Engineering Group

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Weldon Spring Site Remedial Action Project

Remedial Investigation for the Quarry Residuals Operable Unit of the Weldon Spring Site, Weldon Spring Missouri

Revision 1

July 1997

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U.S. DEPARTMENT OF ENERGY
Oak Ridge Operations Office
Under Contract DE-AC05-86OR21548

ABSTRACT

The Weldon Spring Quarry was used for waste disposal by the U.S. Department of Defense and the Atomic Energy Commission form the 1940s through the 1960s. In 1990, a Record of Decision calling for excavation of this waste was signed by the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Energy (DOE) completed removal in 1995. This report provides information developed from characterization of contamination in affected geological media after the waste was removed.

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1 INTRODUCTION

1.1 Scope

The Quarry Residuals Operable Unit is one of four operable units included in the Weldon Spring Site Remedial Action Project (WSSRAP) as registered in the National Priorities List under the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA). The Weldon Spring quarry is located approximately 30 miles west of St. Louis (Figure 1-1) between Defiance and Weldon Spring, in St. Charles County, Missouri. It is 4 miles southwest of the Weldon Spring Chemical Plant site on Missouri Highway 94.

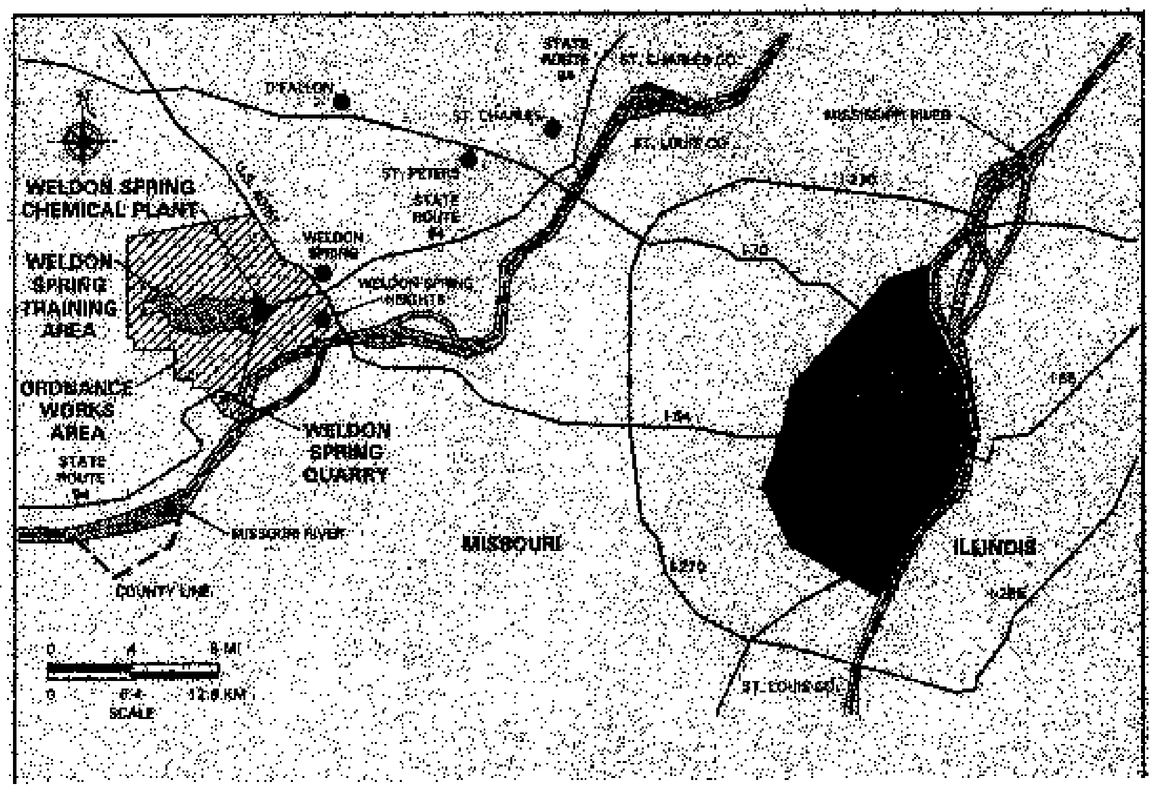

FIGURE 1-1 Location of the Weldon Spring Quarry

The Weldon Spring quarry was excavated into limestone bluffs at the northern edge of the Missouri River alluvial floodplain, which extends approximately 1 mile south to the river. The quarry was used for waste disposal by the Department of Defense and the Atomic Energy Commission from the 1940s through the 1960s. In 1990, a Record of Decision calling for excavation of the bulk waste was signed by the U.S. Environmental Protection Agency (EPA), and removal was completed in 1995.

Through the Quarry Residuals Operable Unit, the Department of Energy (DOE) is addressing radiological and chemical contamination remaining in affected media after excavation of the bulk waste. This report provides information developed from characterization of contamination in these media. In support of the Operable Unit, the *Work Plan for the Remedial Investigation/Feasibility Study -Environmental Assessment for the Quarry Residuals Operable Unit at the Weldon Spring Site* (Ref. 1) was finalized in January 1994 and provided guidance for investigations conducted in support of this remedial investigation report. The work plan also includes detailed discussions of site history, geology, hydrology, and ecology and summarizes analytical data collected prior to 1994. The *Quarry Residuals Sampling Plan* (Ref. 2) also became final in January 1994. Two addenda to the sampling plan, one addressing characterization of the quarry proper and the other addressing resurgent water in the quarry pond and data gaps, were prepared in 1995. This remedial investigation report describes the results of these characterization efforts.

1.2 Authorizing Documentation

This remedial investigation report is prepared to comply with the requirements set forth in 40 CFR 300, *National Oil and Hazardous Substances Pollution Contingency Plan* and the *Environmental Documentation Department Plan* (Ref. 3). For remedial action sites, it is DOE policy to integrate values associated with the *National Environmental Policy Act* (NEPA) into the CERCLA decision-making process. The analyses contained herein address NEPA values as appropriate to the actions being considered for this operable unit.

1.3 Document Organization

This document contains thirteen sections: introductory material is presented in Sections 1 through 3; Sections 4 through 9 are organized by media and contain discussions of results from this remedial investigation. These observations are carried forward to Section 10, where the fate and transport of contaminants are examined as a continuous system. A summary of the baseline risk assessment is presented in Section 11. A summary of major conclusions and a discussion of possible additional investigations are presented in Section 12. References are included in Section 13. Appendices are located in Volume II of this report and contain supporting data and information.

2 BACKGROUND INFORMATION

This section describes the history of waste disposal and remedial activities at the Weldon Spring Quarry.

2.1 Site Description

The Weldon Spring quarry consists of two areas: the quarry proper and the adjacent support facilities area. The quarry proper consists of the 9-acre quarry which was excavated into the limestone bluff of the Missouri River floodplain. Presently, a pond occupies the lowest point of the quarry.

The adjacent 2-acre support facilities area is comprised of the quarry water treatment plant and its associated basins and the facilities utilized during bulk waste removal activities. The facilities include, but are not limited to, trailers, decontamination pad, transfer station, and other ancillary facilities. These facilities are temporary and will be addressed during restoration activities at the quarry.

The quarry is surrounded by the Weldon Spring Conservation Area. The Missouri-Kansas-Texas railroad line formerly passed just south of the quarry. This line has been dismantled and the right-of-way has been converted to the Katy Trail State Park (Katy Trail) which is used for recreational activities. The St. Charles County well field is located southeast of the quarry between the Femme Osage Slough and the Missouri River. This well field is a major source of drinking water for St. Charles County. The closest production well is approximately 0.5 miles from the quarry.

2.2 Site History

In 1941, limestone was mined from the Weldon Spring Quarry and crushed into aggregate that was used for construction of the Weldon Spring Ordnance Works. From 1941 to 1945, the U.S. Department of the Army (Army) produced trinitrotoluene (TNT) and dinitrotoluene (DNT) at the ordnance works and used the quarry, which lies within the former ordnance works boundaries, for disposal of manufacturing wastes. At the end of World War II, the ordnance works was decommissioned. Between 1946 and 1957 the Army disposed of contaminated process residues and building rubble in the 9-acre quarry. In 1955, 200 acres of the ordnance works area were transferred to the Atomic Energy Commission (AEC) for construction of the Weldon Spring Uranium Feed Materials Plant, where uranium ore was processed into uranium metal from 1957 to 1966. The AEC acquired title to the quarry in 1958 and used it from 1960 to 1969 as a disposal area for wastes contaminated with thorium, uranium, and radium. In total, approximately 140,000 cu yd of wastes were placed in the quarry. Table 2-1 summarizes disposal activities; a more complete description is presented in the report, *Remedial Investigations for Quarry Bulk Wastes* (Ref. 4).

TABLE 2-1 Bulk Waste Disposal Activities

DATE	MATERIAL	QUANTITY
1942-1945	Nitroaromatics and Residues. Quarry used for TNT/DNT waste disposal.	unknown
1946	Nitroaromatics and Residues. Quarry used for TNT/DNT waste disposal.	90 tons
1946-1957	TNT Residues. Residues and rubble dumped in deepest part of quarry and in northeast corner.	unknown
1959	Thorium Residues. Disposal of drums containing 3.8% thorium residues. Estimated Ra-228 content of 0.25 Ci.	185 yd^3
Early 1960's	Building Rubble, Equipment, Soils. Demolition rubble from Destrehan Street Plant. Covers approximately 1-acre to depth of 30 ft deep in the deepest part of the quarry. Contains uranium and radium contamination with less than 1 Ci Ra-226.	50,000 yd^3
1963-1965	Thorium and Uranium Residues. Several thousand drums containing thorium and rare earths from Granite City Arsenal. Initially intended for disposal. Much of waste later removed for reprocessing.	unknown
1966	Thorium Residues. Drums and residues from shutdown and cleanup of Weldon Spring Chemical Plant process equipment.	unknown
1966	Thorium Residues. Hundreds of drums brought from Cincinnati by rail. Contain 3% thorium with estimated 1 Ci Ra-228. Placed above water level.	555 yd^3
1966	TNT/DNT Residues. Contaminated rock and soil dumped in northeast corner of quarry covering the Cincinnati thorium residues.	unknown
1968-1969	Uranium and Thorium Residues. Contaminated building rubble and process equipment from Weldon Spring Chemical Plant. Principal sources of radioactivity are Ra-226 and Ra-228.	5,560 yd^3

Source: Ref. 4

After closure by the AEC, the chemical plant was restored to the Army in 1967. In 1971, the Army returned the 51-acre portion of the property containing the raffinate pits to the AEC but retained control of the remainder of the chemical plant area. As successor to the AEC, the Department of Energy (DOE) assumed responsibility for the raffinate pits. In May 1985, the DOE designated the control and decontamination of the Weldon Spring site as a Major Project; it was redesignated as a Major System Acquisition in May 1988. A project office was established in October 1986, and the site is currently under the control of the DOE and is managed by DOE's Project Management Contractor (PMC).

In October 1985, the U.S. Environmental Protection Agency (EPA) proposed to list the Weldon Spring quarry on the National Priorities List (NPL); this listing occurred in July 1987 (Ref. 5). In June 1988, the EPA proposed to expand the listing to include the chemical plant area; this listing occurred in March 1989 (Ref. 6).

Two separate expedited response actions were performed to mitigate the potential threat to the nearby drinking water supply in the St. Charles County well field. These actions included management of the contaminated pond water in the quarry and removal of the bulk waste. First, an Engineering Evaluation/Cost Analysis (EE/CA) was prepared (Ref. 7) to support the decision to treat pond water in a facility constructed adjacent to the quarry and to release the treated water into the Missouri River. A National Environmental Policy Act (NEPA) finding of no significant impact was issued in February 1990, and the water treatment plant became operational in 1992. Second, The *Record of Decision for the Management of the Bulk Wastes at the Weldon Spring Quarry* (Ref. 8) (ROD-BW) was signed by the EPA in September 1990. The ROD-BW specified that the bulk waste was to be removed using conventional construction equipment, transported on a dedicated haul road to the chemical plant, and placed in storage where it was to be maintained until final disposal, as specified by the *Record of Decision for Remedial Action at the Chemical Plant Area of the Weldon Spring Site* (Chemical Plant ROD) (Ref. 9).

Bulk waste excavation began in May 1993 and was completed in October 1995. During this period, approximately 140,000 cu yd of soil and waste material were removed and transported to the chemical plant. Most contaminated soil was removed from the quarry during the bulk waste removal action. Following bulk waste excavation, rock surfaces and fractures were power-washed to remove loose material.

In January 1996, contaminated soil was removed from Vicinity Property 9 (VP-9), which is just south of the quarry, as prescribed in the Chemical Plant ROD (Ref. 9). Remediation of this area generally involved removing the upper 2 ft of soil and soils up to 5 ft in isolated areas where U-238 concentrations exceeded 30 pCi/g. The excavation was backfilled with clean soil to approximately the original grade.

2.3 Physical Setting

The Weldon Spring Quarry is in a unique physiographic setting. It is located near the boundary between the Dissected Till Plain section of the Central Lowlands Physiographic Province and the Salem Plateau Section of the Ozark Plateaus Province, approximately coincident with the commonly accepted southern limit of Holocene glaciation (Ref. 1). This region, with the exception of the Missouri River floodplain, is characterized by narrow ridges and deep valleys incised by short, steep, bedrock-controlled streams. Figure 2-1 is a topographic map of the area surrounding the quarry. Elevations range from 450 ft to 560 ft above mean sea level (Ref. 10). Elevations are highest along a ridge south of the quarry that forms the bluff overlooking the Missouri River floodplain. The floodplain extends from the bluff to the river, a distance of approximately 1 mile. The river forms the southern margin of the quarry study area. The natural relief across the floodplain is less than 12 ft (Ref. 2).

Streams in the immediate vicinity of the quarry include the Femme Osage Creek, the Little Femme Osage Creek, and the Missouri River (Figure 2-1). The original downstream reaches of the Femme Osage Creek and the Little Femme Osage Creek were cut off by the construction of a flood control levee and now form the Femme Osage Slough.

Bedrock in the quarry area is primarily limestone with some shale and dolomite. Bedrock is exposed in the quarry walls and floor and on the steep bluffs along the Missouri River. Upland areas are overlain by 10 ft to 40 ft of silty clay, which is primarily wind-blown, glacially-derived loess and residuum. In the Missouri River floodplain, alluvial deposits occur in stream valleys, coarsen and thicken in the direction of the river, and are as much as 100 ft thick.

2.4 Demographic and Land Use Information

The population of St. Charles County in 1990 was 212,907; 20% of the population lives in the city of St. Charles, approximately 22.4 km (14 mi) northeast of the Weldon Spring site. The population in St. Charles increased by 48% from 1980 to 1990. The two communities closest to the site are Weldon Spring and Weldon Spring Heights, about 3.2 km (2 mi) to the northeast. The combined population of these two communities in 1990 was 1,034 (Ref. 13). No private residences exist between Weldon Spring Heights and the site. Urban areas occupy about 6% of county land, and nonurban areas occupy 90%; the remaining 4% is dedicated to transportation and water uses.

The St. Charles County well field is located approximately 0.5 mi southeast of the quarry. The wells are completed in the Missouri River alluvium and supply a maximum of 22 million gal/day of water for use by 70,000 county residents.

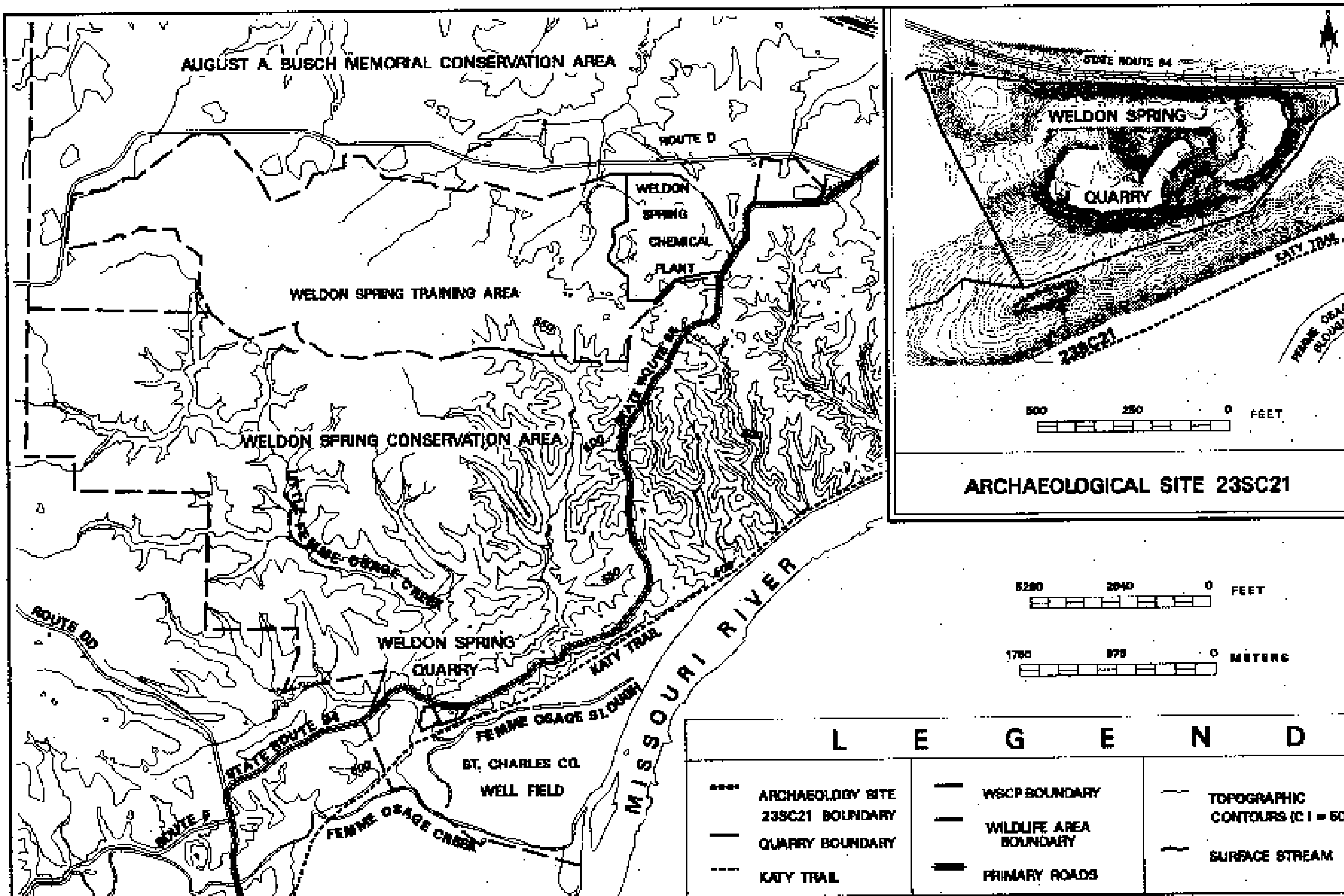

FIGURE 2-1 Topography of the Weldon Spring Quarry Vicinity Showing Archaeological Site 23SC21 and Recreation Facilities

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Most of the land in the quarry area is owned by the State of Missouri. The quarry lies within the Weldon Spring Conservation Area, which covers 7,356 acres. The August A. Busch Memorial Conservation Area and the Howell Island Conservation Area lie to the north and east of the quarry, respectively. All these areas (Figure 2-1) are managed by the Missouri Department of Conservation and are open to the public for fishing, hunting, and other recreational activities. The Katy Trail State Park, which is managed by the Missouri Department of Natural Resources, is a gravel-based public hiking and biking trail that runs along the former Missouri-Kansas-Texas Railroad right-of-way (Ref. 11). This trail passes directly to the south of the quarry.

Access to the quarry is restricted and controlled by the DOE. To the west of the quarry proper, the support facilities for bulk waste excavation are located. These include a water treatment plant, trailers, a parking area, and a haul road.

2.5 Archaeological Investigations

Although no prehistoric or historic remains occur in the quarry proper, archeological surveys have documented the presence of numerous prehistoric and historic sites in the area. In 1989, the WSSRAP conducted a Phase II assessment of Site 23SC21, which is located on the bluff between the quarry and the Katy Trail (Figure 2-1) (Ref. 14), to establish its significance with respect to National Register of Historic Places (NRHP) criteria. The Phase II report recommended that if project modification is not a feasible alternative, Site 23SC21 should be subjected to Phase III mitigation, which includes hand excavation to recover artifacts.

In 1990, a Memorandum of Agreement between the DOE and the Missouri State Historic Preservation Officer (SHPO) was submitted to the Advisory Council on Historic Preservation in Washington, D.C. (Ref. 12). This memorandum stipulated that if any proposed remedial action results in an impact to Site 23SC21, the DOE will ensure that a data recovery plan is developed in consultation with the Missouri SHPO and in accordance with federal regulations (36 CFR Part 800).

2.6 Significant Observations

- The quarry is located at the western edge of a rapidly growing metropolitan area.
- The quarry is near the St. Charles County well field, the source of drinking water for approximately 30% of the residents in the area.
- Any action that disturbs the archeological site on the south quarry rim will require Phase III mitigation.

3 DATA ANALYSES

This section describes the manner in which data supporting the remedial investigation have been grouped, screened, and summarized. The approach to background comparisons and other criteria used for identifying potential contaminants are also presented.

3.1 Data Presentation

Laboratory and field data that form the basis for discussions in this document are grouped by media and location. The data groupings for each medium are described in the appropriate section. Data for these groups are summarized in tables in Appendixes C through H.

Data tables for nitroaromatic compounds and naturally occurring parameters include the number of samples collected (#), the percent of the data that are below the limit of detection (%ND), the mean (Mean), standard deviation (Std), and the upper 95% confidence limit about the mean (UCL95). In cases where insufficient data are available to calculate UCL95 (i.e., only 1 sample), the measured value is presented.

Data tables for anthropogenic compounds other than nitroaromatic compounds are abbreviated because few organic chemicals were detected in any of the quarry media. Only detected compounds are presented in the tables; a complete list of organic analyses is given in Table B.9 of Appendix B. The data summary tables for detected organic chemicals present the number of samples, %ND, and the maximum concentration.

For most parameters, data from 1987 to July 1996 were used to calculate the summary statistics. An additional calculation based on data collected from early 1995 to July 1996 is presented for antimony and nitroaromatic compounds in groundwater. Beginning in 1995, a different, more sensitive method was used to analyze antimony, and source removal, which had a dramatic effect on concentrations of nitroaromatic compounds, was completed by mid 1995.

3.1.1 Substitutions for Values Below the Detection Limit (NDs)

Concentrations of many constituents are commonly below the limit of detection and require a substituted value when used in statistical calculations. If the laboratory provided a qualitative value, this value was used in statistical calculations. If only "ND" was reported, the detection limit was divided by 2 and substituted as the concentration for naturally occurring parameters. This substitution, which is consistent with U.S. Environmental Protection Agency (EPA) recommendations (Ref. 15), accounts for the presence of these parameters in natural environments. Zero was substituted for anthropogenic parameters, which are not expected to be present at any level.

3.1.2 Data Screening

Unabridged data sets, including validation and data review qualifiers, are presented in a separate volume as Appendix J of this document for contaminants of potential concern (COPC) identified in the Baseline Risk Assessment. During the data validation and review process, certain values were rejected. These rejected values were removed from data sets presented in the summary tables and graphs displayed in this document. In addition, ND data with high detection limits were removed from the data sets because of their potential to bias the summary statistics. Screening criteria are presented in Appendix B.

As illustrated in Figure 3-1, data collected by the Weldon Spring Site Remedial Action Project (WSSRAP) pass through a number of review steps before they are permanently stored in WIZARD, the WSSRAP database. First, data are verified to determine if basic performance criteria, such as holding times, chain of custody, and correct supporting documentation, are met. Data are then examined by qualified reviewers to determine if the data set is complete and if there are potential problems. Identified problems are investigated. If examination of the documentation package does not explain suspect data, the problem may be resolved through reanalysis, resampling, and/or validation. If reanalysis or resampling are not possible, and validation does not detect the source of the problem, the reviewer may apply a qualifier to the data. If the reviewer believes a suspect data point cannot reflect conditions in the location sampled and use of the data would misrepresent these conditions, the reviewer may petition the WSSRAP Data Review Qualification Team to apply reviewer-rejected qualifiers to the data. If the team concurs with the reviewer's findings, the datapoint is given a qualifier that indicates reviewer-rejected data that likely reflect sampling, analytical, or transcription errors and are not recommended for use. Qualifiers and criteria for rejecting data are defined in Appendix B.

For these investigations, data collected prior to activation of reviewer qualifiers in 1995 were also re-examined and qualified, where necessary. The total number of reviewer-rejected data comprise less than 1% of the unabridged data set.

3.2 Identification of Contaminants

Sections 6, 7, and 9 of this document identify potential contaminants in soil, surface water and sediment, and groundwater in the quarry area. A contaminant is defined as any chemical species that does not occur naturally or occurs at levels that exceed those of the natural environment. Based on this definition, identification of anthropogenic contaminants is relatively straightforward; however, identification of naturally occurring contaminants requires comparison with data from a suitable background location.

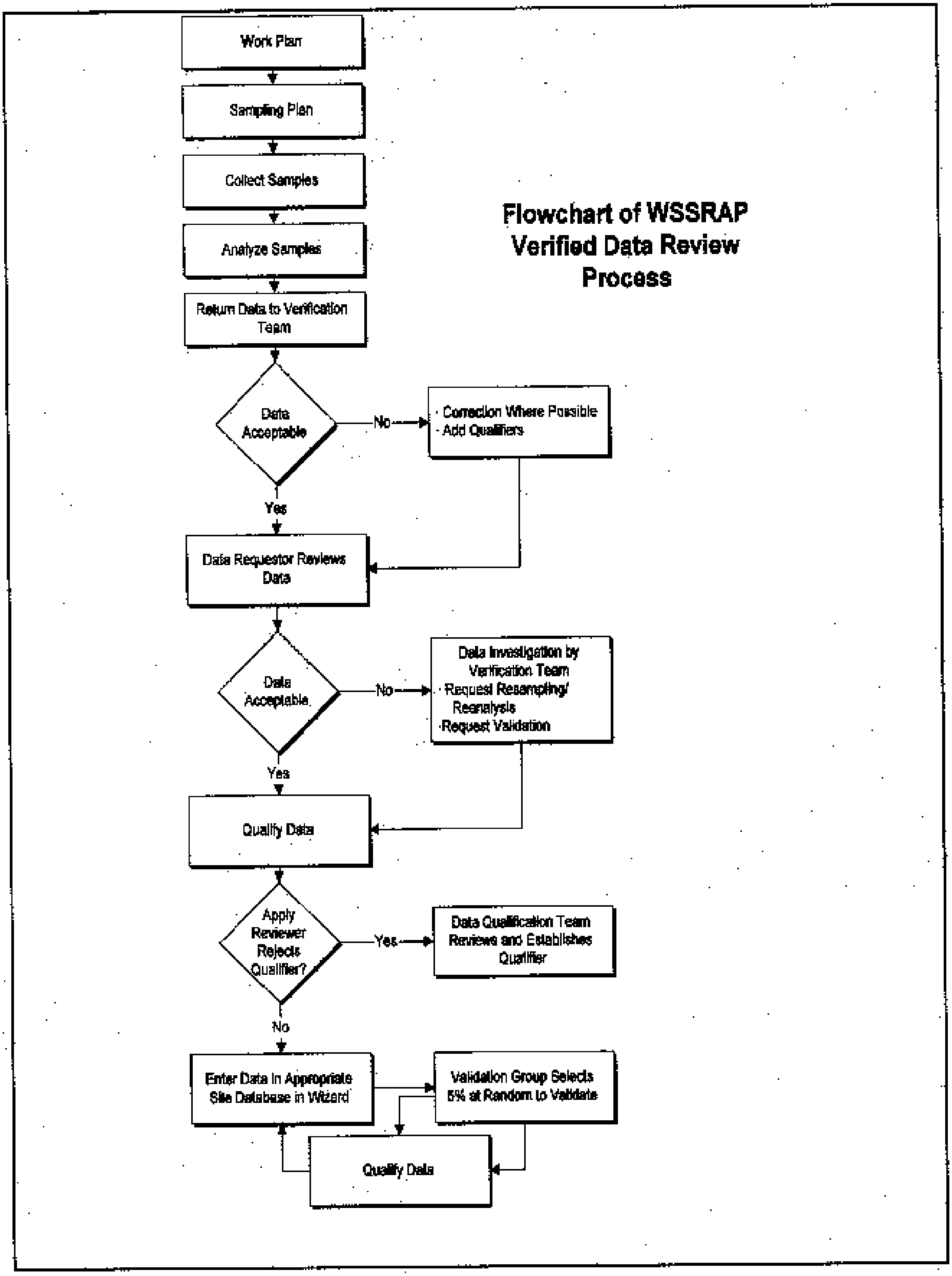

FIGURE 3-1 Flow Chart of WSSRAP Data Review Process

3.2.1 Background Comparisons

Background comparisons for naturally occurring parameters are illustrated in bar graphs in Sections 6, 7, and 9 that show UCL95 for the sample groups ($UCL95_S$) divided by UCL95 for the derived background ($UCL95_B$) (i.e., value calculated for background samples) for each parameter. This ratio results in a unitless number that indicates the amount by which $UCL95_S$ exceeds $UCL95_B$. If 100% of the sample group values are below the limit of detection, this ratio is set to one.

Strict interpretation of the background comparison ratio would label any parameter with a ratio greater than 1 as a contaminant; however, in many instances this label would be unwarranted. An extremely low $UCL95_B$ relative to $UCL95_S$ could occur if insufficient data were collected to adequately characterize background variability or if detection limits for seldom detected parameters were lower for the background data than the sample group data. To avoid unnecessary discussion of parameters that are marginally above the derived background, the following sections focus on parameters that exceed two times this level. Examination of background comparison ratios ($UCL95_S/UCL95_B$) showed a natural breakpoint at 2, as shown on Figure 3-2. Above this level, clustering of comparison ratios decreased, indicating that deviation from derived background was more likely to reflect true differences from natural background. In addition, a U.S. Geological Survey (USGS) report (Ref. 65) shows natural variability in concentrations of many elements in soils in this region. The derived background values from the remedial investigation data were at the low end or below the concentration range for many elements reported by the USGS.

Special emphasis is given to groundwater and surface water parameters that exceed water quality standards and to soil and sediment parameters that exceed the screening guidelines presented in the Work Plan (Ref. 1). These standards and guidelines are presented in Table 3-1. Where indicated, parameters that exceed any of these criteria in a subgroup within any major grouping may also be included in the discussion. None of these criteria impact calculations performed for the Baseline Risk Assessment, which examines all parameters that exceed background.

3.3 Significant Observations

- Data are grouped by location and media.
- Reviewer and validation rejected data have been removed from data sets presented in summary tables and graphs.
- Detection limit divided by 2 is substituted for "ND" for naturally occurring parameters. Zero is substituted for "ND" for anthropogenic parameters.

- Contaminant discussions in this report focus on naturally occurring parameters that exceed two times background and anthropogenic parameters greater than zero. Special emphasis is given to parameters that exceed water quality standards (groundwater and surface water) or screening guidelines presented in the work plan (soil and sediment).

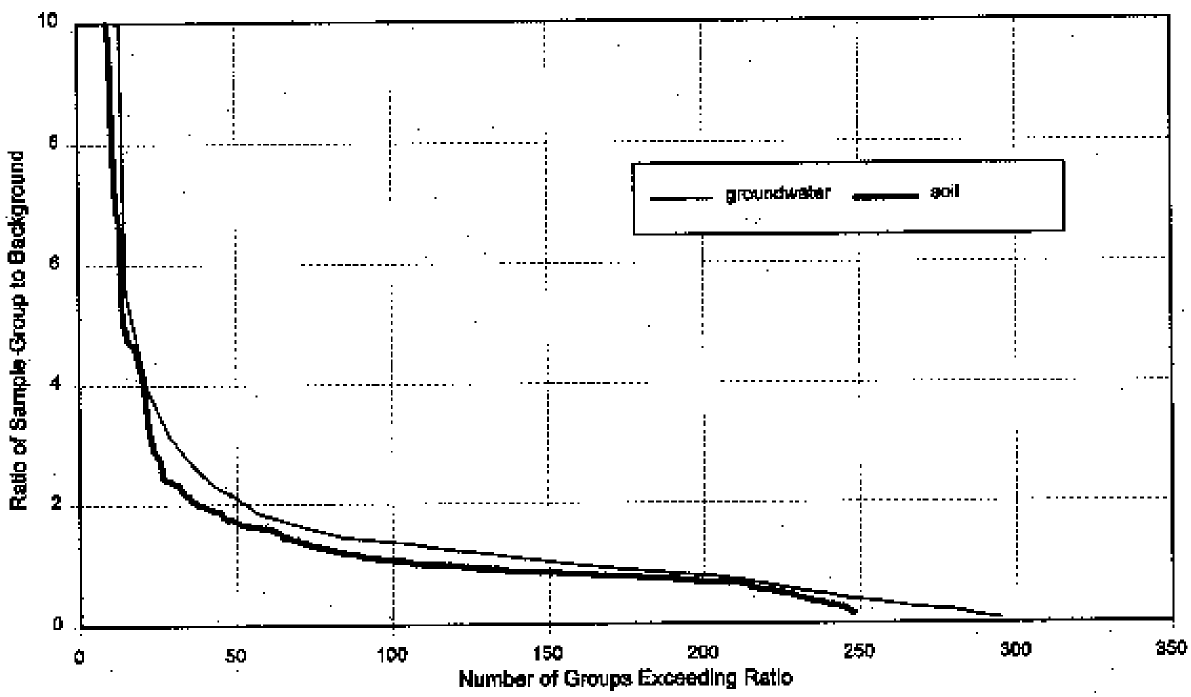

FIGURE 3-2 Distribution of Sample to Background Ratios ($UCL95_S/UCL95_B$)

TABLE 3-1 Screening Guidelines for Surface Water, Groundwater, Soils, and Sediments

PARAMETER	WATER QUALITY STANDARD	REF	SCREENING GUIDELINES FOR SOIL CONCENTRATIONS	REF
METALS	µg/l		µg/g	
Aluminum	200	a	N/A	--
Antimony	6	e	2,100	g
Arsenic	50	e	140	h
Barium	2,000	e	370,000	g
Beryllium	4	e	58	h
Cadmium	5	e	5,300	g
Chromium	100	e	24,000	g
Cobalt	1,000	f	N/A	--
Copper	1,000	a	210,000	g
Iron	300	a	N/A	--
Lead	15	f	N/A	--
Lithium	N/A	--	110,000	g
Manganese	50	a	N/A	--
Mercury	2	e	1,600	g
Molybdenum	N/A	--	27,000	g
Nickel	100	e	110,000	g
Selenium	50	e	27,000	g
Silver	50	f	27,000	g
Thallium	2	f	370	g
Vanadium	N/A	–	37,000	g
Zinc	5,000	a	N/A	--
ANIONS	mg/l		mg/kg	
Chloride	250	a	N/A	--
Fluoride	4	e	N/A	–
Nitrate (as N)	10	e	N/A	--
Sulfate	250	a	N/A	--

TABLE 3-1 Screening Guidelines for Surface Water, Groundwater, Soils, and Sediments (Continued)

PARAMETER	WATER QUALITY STANDARD	REF	SCREENING GUIDELINES FOR SOIL CONCENTRATIONS	REF
NITROAROMATIC COMPOUNDS	μg/l		μg/g	
2,4-DNT	0.11	f	N/A	–
2,6-DNT	1.3	c	N/A	–
2,4,6-TNT	2	f	N/A	--
TNT/TNB	N/A	--	1,000	i
RADIONUCLIDES	pCi/l		pCi/g	
Adj. Gross Alpha *	15	d	N/A	--
Ra-226	5 (Total)	e	14	j
Ra-228		e	28	j
Rn-222	300	d	N/A	--
Th-230	N/A	–	420	h
Th-232	N/A	--	28	J
U-238	N/A	--	240	h
Total Uranium **	13.6	d	N/A	–

* (excluding Ra-226, Rn-222, & U)
** Relationship between pCi and μg based on Site-Specific Conversion factor
a Secondary MCL, EPA Drinking Water Regulations and Health Advisories (1996)
b Action Level, EPA Drinking Water Regulations and Health Advisories (1996)
c Work Plan (10-5 risk level)
d Proposed EPA Drinking Water Standards, 40 CFR (1991)
e MCL, EPA Drinking Water Regulations and Health Advisories (1996)
f MCL, Missouri Quality Standard for Groundwater or Surface Water Used as Drinking Water Supply, 10 CSR 20-7 (10/31/96)
g 0.5 hazard quotient, Quarry Residuals Work Plan
h 10^{-5} carcinogenic risk, Quarry Residuals Work Plan
i 10^{-6} carcinogenic risk level (lower level used because immunoassay technique, which was primary screening tool for nitroaromatic compounds, measures combined TNT/TNB)
j 10^{-4} carcinogenic risk (higher level used because 10^{-5} level is equivalent to background concentrations, Quarry Residuals Work Plan

4 METEOROLOGICAL CONDITIONS AND AIR MONITORING PROGRAM

This section summarizes the meteorological conditions in the quarry area and presents the results of the air monitoring program conducted at the quarry since 1987 by the Weldon Spring Site Remedial Action Project (WSSRAP).

4.1 Regional and Local Meteorological Conditions

The National Oceanic and Atmospheric Administration (NOAA) records local and regional climatic and meteorological data at Spirit of St. Louis Airport and St. Louis-Lambert Field International Airport. Additional local information is available from the project meteorological station at the Weldon Spring Chemical Plant site. Table C-1 of Appendix C lists regional and site meteorological studies.

The regional climate is continental with moderately cold winters and warm summers. On average, temperatures below 32°F are recorded 111 days per year, and temperatures above 90°F are recorded 35 to 40 days per year. Alternating warm/cold, wet/dry air masses often converge and pass eastward through the area, resulting in frequent weather changes (Ref. 4). Prolonged periods of very cold or very hot weather are unusual.

Data from the site meteorological station show prevailing winds are from the south and south-southwest during the spring and summer, from the south during the fall, and from the northwest and north-northwest during the winter. Average wind speed is 4.9 mph during the summer and 8.1 mph during the winter.

4.1.1 Precipitation

Historic precipitation data measured at St. Louis Lambert Field from 1964 through 1995 show an annual average of approximately 37 in. (Ref. 16). Historical data indicate that more than half the annual precipitation falls between March and July, although intense storms can occur in any month. Summer rains are frequently in the form of thunderstorms and often associated with hail and high winds (Ref. 4). December, January, and February are generally the driest months. St. Louis area records from 1941 through 1970 indicate measurable precipitation (>0.01 in.) occurred on an average of 109 days per year (Ref. 4). Snow has fallen as early as October and as late as May. Data recorded at Lambert Field between 1964 and 1994 indicate the mean annual snowfall is 19.8 in., which typically occurs from December through March (Ref. 4).

Precipitation data measured in the Weldon Spring area for the period 1983-1996 are in Table C-2. The mean annual precipitation for this period is approximately 42 in. The maximum monthly precipitation recorded was 13.49 in. in September 1993 which contributed to the flooding of 1993, and the minimum was 0.04 in. in September 1983.

4.1.2 Evaporation/Evapotranspiration

Data compiled from 1956 through 1980 indicate that annual average free water surface evaporation and evapotranspiration in the region are close to annual average total precipitation, approximately 37 in. and parallel average monthly precipitation, with the highest values occurring during summer and the lowest in winter (Ref. 4). The coefficient of evapotranspiration for the area near the site ranges from 0.72 to 0.74 (Ref. 4). Site-specific evaporation/evapotranspiration data recorded for April through October in 1983 and 1984 indicate total evaporation ranges from 31 in. to 38.3 in. per year (Ref. 80).

4.2 Site Air Monitoring Program

In 1987, an environmental air monitoring program was established to detect radioactive airborne particulates, radon, thoron, asbestos, and gamma radiation emanating from the Weldon Spring quarry. This program was based on previous characterization data and knowledge of disposal activities. Radon and gamma radiation monitoring were also performed at Vicinity Property 9 located south of the quarry prior to its remediation in January 1996.

Prior to bulk waste removal, contaminated soils in the quarry were covered with vegetation or standing water, limiting releases to the atmosphere. During bulk waste removal, much of the vegetation was removed, and the water level of the quarry pond was gradually lowered. This, along with the operation of excavation equipment, contributed to increased radon and airborne radioactive particulate emissions during this period. Contamination remaining after bulk waste removal is primarily limited to fractures and depressions in the quarry walls and floor and a small soil area in the northeast corner, as described in Section 6. This residual contamination has the potential to elevate radioactive airborne particulate and radon concentrations in the quarry above natural background levels.

4.2.1 Guidelines/Criteria

Radiation protection requirements for radon, radioactive airborne particulates, and gamma radiation exposure for Department of Energy (DOE) activities are established in DOE Order 5400.5, *Radiation Protection of the Public and Environment* (Ref. 17). This regulation requires that public exposure to radiation sources from DOE activities shall not cause an annual committed effective dose equivalent (CEDE) greater than 100 mrem. The exposure of the public to radioactive materials from inhalation of airborne particulates shall not exceed an annual CEDE of 10 mrem.

For interim storage, radon concentrations in the atmosphere above facility surfaces or openings may not exceed (1) 100 pCi/l at any given point, (2) an annual average concentration of 30 pCi/l over the facility site, and (3) an annual average concentration of 3 pCi/l at or above any location outside the facility site.

The derived concentration guides (DCGs) for inhalation of various radionuclides are specified in DOE Order 5400.5 (Ref. 17). The DCGs are based on a CEDE of 100 mrem per year. The DCG for both Rn-222 and Rn-220 (thoron) is 3 pCi/l. For airborne particulates, a representative DCG was calculated based upon the average radioactivity content and average solubility of the radionuclides present. The DCG for the quarry is 5.03×10^{4} μCi/ml.

Although ambient air criteria have not been established for airborne asbestos fibers, the clearance air limits of 0.01 fibers per cubic centimeter of air (f/cc) established by the U.S. Environmental Protection Agency (EPA) for occupancy of school buildings was used to evaluate asbestos monitoring data.

4.2.2 Air Monitoring Network

4.2.2.1 Background Air Monitoring. The WSSRAP has monitored background concentrations for radioactive airborne particulate concentrations, radon/thoron concentrations, and gamma radiation exposures since 1987. The current background monitoring locations are shown in Figure 4-1. Between 1990 and 1995 additional stations in the August A. Busch Conservation Area were also used. Annual average results for all background locations are listed in Appendix C (Table C-3).

4.2.2.2 Quarry Monitoring Locations. The air quality monitoring network for the quarry is shown on Figure 4-1. With the exception of one location within the quarry, monitoring sites are on the perimeter of the quarry. Network equipment consists of alpha-track and modified alpha-track radon monitors, high- and low-volume radioactive airborne particulate monitors, thermoluminescent dosimeters (TLDs) to detect gamma radiation, and low-volume pumps for asbestos sampling.

Natural airborne radon (i.e., Rn-222 and Rn-220) concentrations fluctuate with both soil and meteorological conditions. The amount of radon that enters the atmosphere is a function of the radium concentrations in the soil, soil moisture content, soil porosity, soil density, and atmospheric conditions. Variations in soil moisture content are primarily responsible for changes in airborne radon concentrations.

Radon has been monitored at the quarry since 1987. The initial monitoring network consisted of five stations (RD-1001 through RD-1005) containing pairs of alpha-track radon

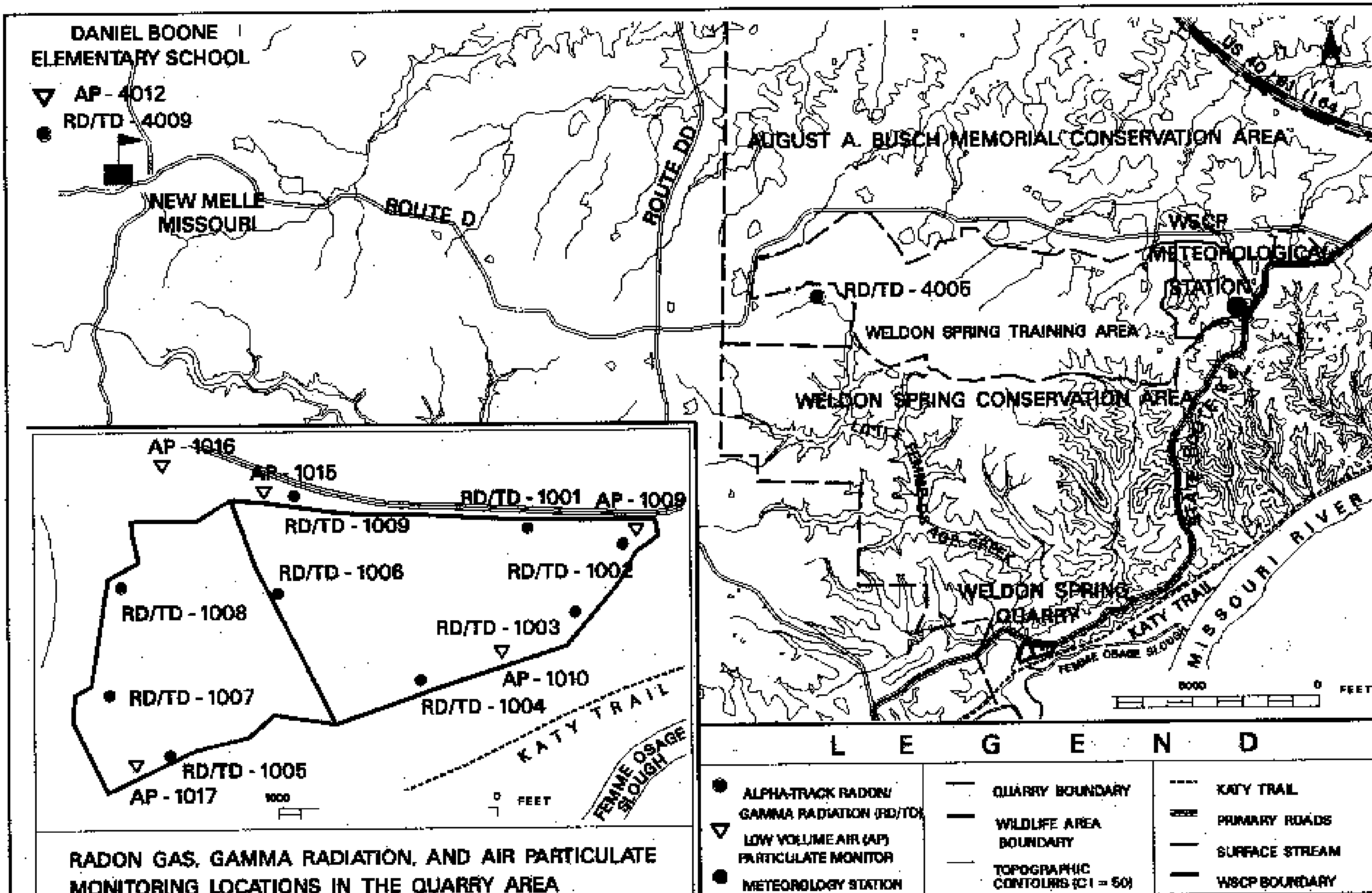

FIGURE 4-1 Locations of Background and Quarry Air Monitoring Stations

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detectors, as shown on Figure 4-1. The use of monitoring Station RD-1001 was discontinued in 1993; Stations RD-1007 and RD-1008 were added in 1992; and RD-1009 was added in 1993.

In 1994, modified alpha-track radon detectors were installed in tandem with existing alpha-track radon detectors at RD-1002, RD-1006, and RD-4009 (background location). The modified alpha-track detectors filter Rn-220 (thoron) allowing calculation of both radon and thoron using a method developed by Pearson (Ref. 18).

Natural radioactive airborne particulate concentrations are affected by the amount of radioactivity in the soil, soil moisture, atmospheric dispersion, and geologic conditions. The monitoring network for radioactive airborne particulates includes five permanent stations (AP-1009, AP-1010, AP-1015, AP-1016, and AP-1017) located on the perimeter of the quarry as shown on Figure 4-1. The air samplers are low volume carbon-vane, oil-free vacuum pumps operated at a rate of approximately 40 liters/min. Samples are collected weekly and analyzed for gross alpha concentrations.

Gamma radiation levels are affected by radionuclide concentrations in the soil, variations in cosmic radiation, and ground surface density (e.g., rock vs soil). Prior to 1995, gamma radiation was monitored at nine locations on the quarry perimeter using environmental TLDs (Figure 4-1). The number of monitoring locations was reduced to four in 1995. TLDs measure the ambient gamma radiation and are analyzed by the vendor on a quarterly basis.

Airborne asbestos was sampled at five locations on the quarry perimeter using a 25 filter cassette and a low-volume pump operated at 1 liter/minute. Samples were collected weekly and analyzed by phase contrast microscopy (PCM). If PCM analysis indicated a concentration above the site action level (0.01 fibers per cubic centimeter of air), the sample was resubmitted for asbestos analysis by transmission electron microscopy. In 1994, monitoring station AP-1015 was discontinued and AP-1016 was established. Monitoring station AP-1026, was monitored in 1995 only.

4.2.3 Results of Monitoring

Annual average radon concentrations from 1987 to 1996 for the nine monitoring stations are summarized in Appendix C (Table C-4). Historically, monitoring station RD-1002 has yielded the highest radon concentrations. The maximum quarterly concentration of 9.2 pCi/l occurred at this station in the first quarter of 1994 during bulk waste removal activities in the vicinity of the monitor. Measurements collected during the first and second quarters of 1996 indicate radon concentrations have returned to natural background levels.

Thoron monitoring at the quarry was initiated in the third quarter of 1994 at RD-1002 and in the fourth quarter at RD-1006. Thoron concentrations are summarized in Appendix C (Table C-5). RD-1006 has yielded background concentrations since its establishment in 1994. RD-1002 showed elevated thoron levels during bulk waste excavation in the vicinity of the monitor. Since the completion of bulk waste removal, 2nd Quarter 1996 results at RD-1002 have indicated thoron concentrations slightly above background. Thoron will continue to be monitored quarterly at this location as part of the WSSRAP environmental monitoring program. All other thoron monitoring following bulk waste removal indicates natural background levels.

Radioactive airborne particulates have been monitored since 1989. The annual averages for long-lived gross alpha concentrations at five permanent low volume airborne particulate monitoring stations are summarized in Appendix C (Table C-6). In 1989 and 1990, the monitoring stations yielded some weekly sample concentrations that were less than the lower limit of detection (LLD); however, the LLD was used to calculate the annual average. This resulted in the actual average being less than the calculated average. Elevated levels of radioactive airborne particulates were detected in 1994 and 1995 during the main phase of bulk waste removal activities. Airborne particulate levels decreased in 1996 and currently, are similar to pre-bulk waste removal concentrations (i.e., background levels).

Results from gamma radiation monitoring are summarized in Appendix C (Table C-7). Prior to bulk waste removal, statistical analysis of gamma radiation results indicated that at the 95% confidence level, several quarry monitoring stations showed annual results that were greater than background levels. Post bulk waste removal results appear to be at background levels.

Asbestos monitoring results are summarized in Appendix C (Table C-8). All asbestos monitoring stations at the quarry yielded background concentrations before and during bulk waste removal. Asbestos monitoring was discontinued in 1996.

4.3 Significant Observations

- Precipitation, which averages approximately 42 in./yr, is greatest in the summer and spring.

- Evapotranspiration rates are approximately equal to precipitation rates.

- Rn-222, gamma radiation, radioactive airborne particulates, and asbestos are presently at background levels and are below DOE protection criteria.

- Rn-220 (thoron) exceeds background at one location on the northeast corner of the quarry proper.

5 ECOLOGICAL INVESTIGATIONS

This section presents results of surveys conducted to characterize ecological communities and to determine the potential impacts, if any, from quarry wastes. Characterization activities included vegetation surveys, threatened and endangered species surveys, and wetland delineation as defined in the sampling plan (Ref. 2).

5.1 Previous Studies

Available background information regarding flora and fauna was reviewed prior to beginning ecological characterization. A summary of existing information from previous surveys is presented in the following sections.

5.1.1 Flora

The quarry is located in the bluestem Prairie Oak-Hickory Forest Mosaic subsection of the Prairie Parkland Province (Ref. 14). This province is characterized by dense to open riparian woodlands interspersed with upland prairie. Today, much of the province has been converted to agricultural fields, and remnants of the prairie are rare in Missouri (Ref. 19). Prairie habitats are not present near the Quarry Residuals Operable Unit area.

The quarry rim and surrounding area are primarily slope forest and bottomland forest. A portion of the natural bluff, with a height of 100 ft, separates the quarry from the Missouri River and its floodplain to the south. Slope forests along the bluff include deciduous trees such as oaks and hickories. Disturbed roadside habitat is found along the Katy Trail which runs directly to the south of the bluff.

In the Missouri River floodplain, which lies to the south of the quarry, agricultural fields are maintained by the Missouri Department of Conservation (MDC) under share-cropping agreements. Portions of these crops are left in the fields for wildlife forage. Corn, soybeans, and milo are the primary crops.

Numerous aquatic habitats are present in the vicinity of the quarry and in the neighboring Weldon Spring Conservation Area. These include the Missouri River, the Little Femme Osage Creek, the Femme Osage Creek, the Femme Osage Slough, and numerous small unnamed tributary streams. Bottomland forests in these habitats include tree species such as eastern cottonwood, silver maple, and sycamore. Periodic flooding and fluctuations in water levels are common in these areas and favor the growth of water tolerant species such as silver maple.

5.1.2 Fauna

Fauna are diverse in the area surrounding the quarry. The area supports a variety of animals common to deciduous forests, agricultural areas, and aquatic habitats. According to the MDC, 25 amphibian, 47 reptilian, 29 mammalian, and 299 avian species occur in St. Charles County (Ref. 20). Species commonly observed within and near the quarry include eastern grey squirrels, raccoons, red fox, and deer mice. The surrounding area is managed for game species such as white-tailed deer, mourning dove, and eastern cottontail rabbit. Three-toed box turtles and skinks are frequently encountered in vegetation on the slope forest floor.

Aquatic habitats in the quarry vicinity also support a variety of fauna. Waterfowl such as wood ducks and Canada geese have been sighted on the Femme Osage Slough, along with red-eared sliders, great blue herons, and beavers. The MDC has recorded more than 105 species of fish in St. Charles County (Ref. 20). Fish surveys of the Femme Osage Slough have recorded carp, catfish, gar, sunfish, crappie, and a variety of minnows and shiners. A total of 12 fish species have been observed in Little Femme Osage Creek (Table D-1 of Appendix D).

Several species classified as Federal and State rare or endangered occur in St. Charles County and are listed in Table D-2 of Appendix D. No designated critical habitats for these species exist near the quarry (Ref. 21). The Howell Island Conservation Area, across the Missouri River from the quarry, provides an important night roost for wintering bald eagles (a Federal listed threatened species). The pallid sturgeon, a Federal listed endangered species, has been reported in the Missouri River near the quarry. Sturgeon chub and sicklefin chub, listed as Federal Category 2, have been recorded in the Missouri River downstream of the quarry.

The MDC reports 15 State endangered, 17 State rare, and 10 State "special-concern" species within St. Charles County (Refs. 22 and 23). The Cooper's hawk and wood frog, both State rare species, have been reported at the Weldon Spring Conservation Area. The wood frog also has been observed in the deciduous forest area to the north of the quarry (Ref. 24). The northern harrier, loggerhead shrike, Swainson's hawk, and bald eagle have been observed within the Weldon Spring Conservation Area. The Blanding's turtle, a State endangered reptile, although not observed at the Weldon Spring Conservation Area, has been sighted at the Busch Conservation Area approximately 4 miles north of the quarry.

5.2 Previous Investigations, Major References, Other Data Sources

A number of ecological surveys have been conducted in the area of the Quarry Residuals Operable Unit. A brief synopsis of each study, including the scope, summary of results, organization responsible for the study, and references is in Appendix D (Table D-3). Populations and community structures within these groups of organisms have been adequately characterized;

therefore, additional surveys of these biological groups were not made a part of the remedial investigation for this operable unit.

In summary, these studies provided the following observations:

- No differences observed in the contaminated and reference aquatic communities as studied for fish, turtles, benthic invertebrates, and zooplankton.

- Biouptake of uranium in the aquatic community is occurring only in fish, but not at levels which would pose a threat to human health.

5.3 Description of Tasks for Remedial Investigations

Ecological characterization activities were identified in the *Work Plan for the Remedial Investigation/feasibility Study - Environmental Assessment for the Quarry Residuals Operable Unit* (Ref. 1) and *Quarry Residuals Sampling Plan* (Ref. 2) to facilitate comparison of ecological conditions in the area of the operable unit with those of background locations. Some of these activities, as described in Appendix D (Table D-4), were not completed due to spring and summer flooding in 1993, 1994, and 1995. The flooding not only kept surveys from being conducted while areas were covered by water, but it strongly impacted the terrestrial and wetland habitats and biota. Because work was disrupted for three consecutive years, it was determined that additional data would be biased by the flooding and would not yield meaningful information. Figure 5-1 shows study and reference areas.

5.4 Summary of Ecological Results

The following sections summarize the results from the ecological activities.

5.4.1 Herpetofauna Survey Results

Herpetofauna surveys were conducted to determine if State or Federal listed reptiles or amphibians inhabit potentially contaminated areas in the vicinity of the quarry. The richness and relative abundance of herpetofauna near the quarry and vicinity were compared to those at the Hamburg Quarry, approximately 1.5 miles to the northeast, which was used as a reference location. Figure 5-1 shows the locations of the study areas (T-1 and T-2) and the reference location (RT-1).

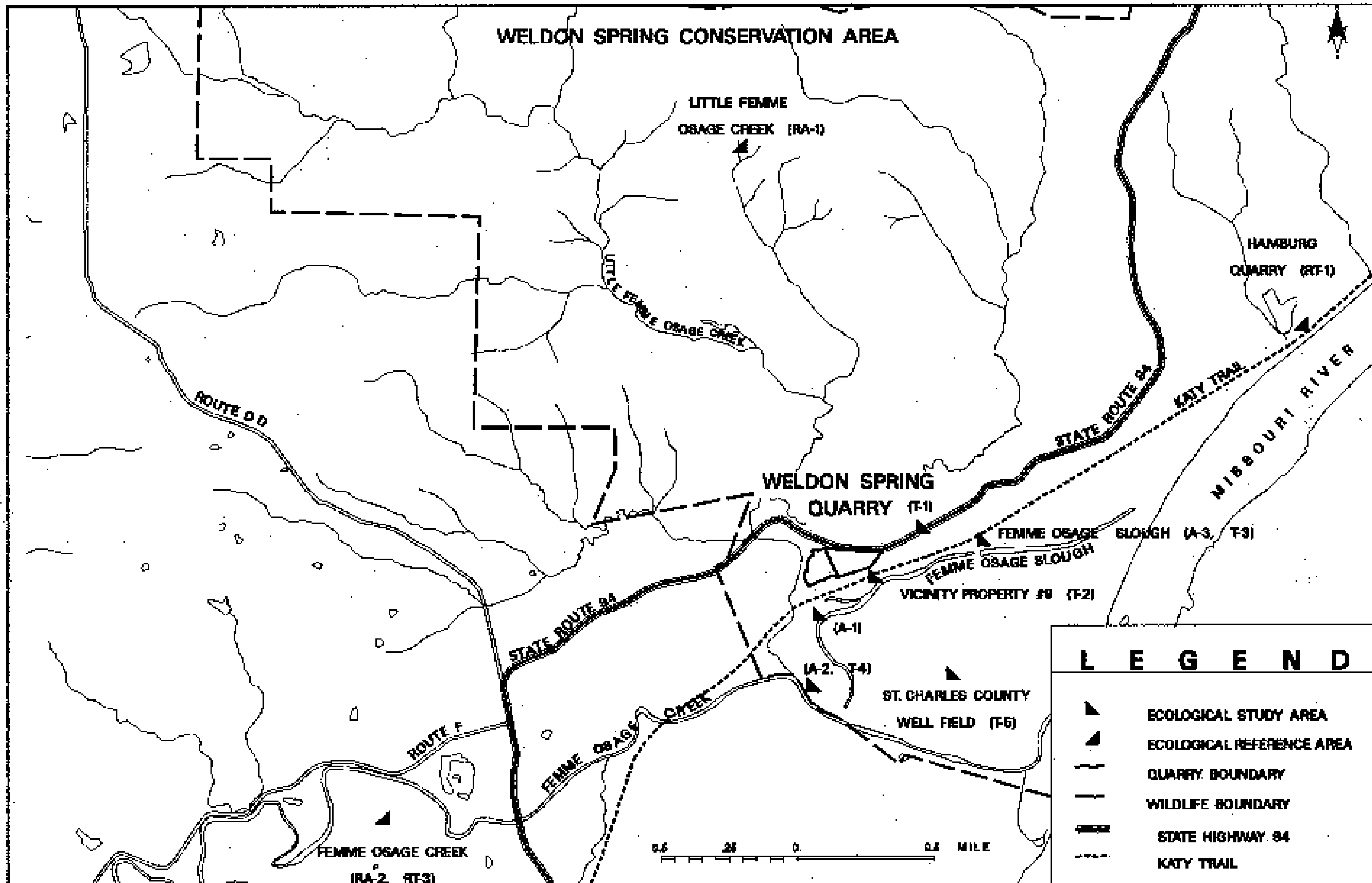

FIGURE 5-1 Locations of Ecological Study and Reference Areas

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No State or Federal listed species were found during these surveys. Survey data were collected by visual techniques (sighted or caught by hand), audio techniques, and by capture within shelter/trap arrays. A total of 15 different species were found within the study locations, and six species were found at the background location. Common species were the gray treefrog, five-lined skink, and ground skinks. The species observed were typical of the habitats where they were found. The species observed at both study locations and the reference location are summarized in Appendix D (Table D-5).

5.4.2 Vegetation Survey Results

Vegetation surveys were conducted to characterize plant communities within the operable unit and its vicinity. The survey data were then used to:

1. Compare vegetation near the quarry to reference locations.

2. Compare percent cover, cover class, and other parameters near the quarry with these characteristics at reference locations.

3. Determine if any State or Federal listed species are present within the quarry area.

4. Provide a preliminary evaluation of faunal food resources which could be contaminated.

Surveys were conducted in the following areas (see Figure 5-1 for locations):

- The upland area between the south rim of the quarry and the Katy Trail (Study Area T-1: 24 sampling stations along six transects).

- The upland area east of the Hamburg Quarry north of the Katy Trail (Study Area RT-1: 24 sampling stations along five transects).

- The lowland area at Vicinity Property No. 9 (VP-9) (Study Area T-2: 31 sampling stations along three transects).

- The lowland area along the southwest edge of the Femme Osage Slough (Study Area T-3: 24 sampling stations along two transects).

- The lowland area along the east edge of the Femme Osage Creek (Study Area T-4: 30 sampling stations along two transects).

The following vegetative layers were identified and tabulated during the surveys:

- Trees with trunk diameter at breast height (DBH) greater than 10 cm (characterized using point-quarter method).

- Tree saplings and shrubs with trunk/stem DBH less than 10 cm (using a 2 m^2 quadrat).

- Vines (using a 2 m^2 quadrat).

- Herbaceous vegetation (using a 1 m^2 quadrat).

Visual surveys for the presence of listed plant species were also conducted during the routine vegetation surveys. Identification of potential faunal food resources was to be based on observed plant species and whether the plants (or portions thereof) are food sources for wildlife.

Initial field activities were conducted during May and June 1995. Heavy precipitation caused extensive flooding of the Missouri River during surveys of the lowland areas and prevented completion of surveys for Study Areas T-2, T-3, T-4, and the related reference areas. The only portion of the planned surveys completed was associated with the upland study areas (T-1 and RT-1). Because the surveys were conducted early in the growing season, herbaceous layers were just beginning to form. Therefore, herbaceous vegetation in most sampling quadrats represented an insignificant percentage of the ground cover (which usually consisted of leaf litter at the time of sampling).

The number of tree and sapling/shrub species observed in Study Areas T-1 and RT-1 are listed in Appendix D (Tables D-6 and D-7) Both areas are mature oak/hickory forests, although the dominant oak and hickory species in each area are different. The dominant trees at Study Area T-1 are northern red oak and mockernut hickory, while the dominant trees at Study Area RT-1 are persimmon, black oak, and bur oak. The understory communities (i.e., saplings, shrubs, and vines) at both T-1 and RT-1 are typical of oak/hickory forests being dominated by dogwood, redbud, elm, black oak, sumac, trumpet creeper, and various grapes. Species diversity and community equality were evaluated using the Shannon Index and Mann-Whitney test, respectively (Appendix D [Tables D-6 and D-7]). These tests indicated that there are no significant differences between the tree and sapling/shrub communities in the quarry and the reference area.

In lowland study areas (T-3 and T-4), only tree data were collected, whereas data are available for all four vegetative layers at Study Area T-2. Because data associated with comparable reference areas could not be collected, no formal evaluations could be made. In summary, the tree communities at each of the three lowland study areas appear to be typical of

Missouri floodplain forests, dominated by common species such as cottonwood, silver maple, box elder, green ash, and various willows.

State and Federal listed plant species were not observed during the routine vegetation surveys. Plant species that represent potential food resources for local wildlife are identified in Appendix D (Tables D-6 and D-7). Typically, wildlife food sources from these plants consist of fruits, nuts, and seeds, and occasionally tender twigs and shoots. In addition, most of the common vines in the study areas, such as Virginia creeper, trumpet creeper, bittersweet, and several species of grape, are an important food source for songbirds, upland game birds, deer, and small mammals.

5.4.3 Threatened and Endangered Species Survey Results

Threatened and endangered species surveys were conducted for four listed species that have been observed in the area of the Quarry Residuals Operable Unit to determine if the area was being utilized for feeding, nesting, and/or roosting activities. These species include the bald eagle, loggerhead shrike, Swainson's hawk, and northern harrier.

The only State or Federal listed species observed during these surveys within the area of the operable unit was the bald eagle. The surveys were conducted along the St. Charles County well field levee near the boat ramp, which provided a clear view of the Missouri River, Howell Island (a known wintering area for bald eagles), and the St. Charles County well field. Bald eagles were observed roosting on Howell Island and periodically in trees along the levee of the well field. Many individuals were observed flying along the Missouri River, probably foraging for food. No individuals were observed flying, roosting, or foraging within the well field. Data collected during bald eagle surveys are summarized in Appendix D (Table D-8).

5.4.4 Wetland Delineation

Wetland delineations have been initiated along Femme Osage Creek, Little Femme Osage Creek, and the Femme Osage Slough in accordance with the U.S. Army Corps of Engineers guidelines (Ref. 25). These areas have been identified as wetlands on the U.S. Fish and Wildlife Service National Wetlands Inventory map (Ref. 26).

Femme Osage Slough

Open waters associated with the Femme Osage Slough are classified by the National Wetlands Inventory as unconsolidated bottom, lower perennial riverine wetland, or permanently flooded wetlands (Ref. 26). The slough supports a diverse aquatic community including numerous macroinvertebrate, amphibian, and fish species. Potential jurisdictional wetlands are located at the end of the northwest arm where hydrophytic vegetation occurs along the banks of a shallow expansion of the slough. Dominant plant species on the lower shallow slope include false pimpernel, cottonwood seedlings, and arrowhead. Slightly higher on the bank, the dominants include purple ammannia, beggar-ticks, flatsedge, and love grass. Jurisdictional wetland determination would require evaluation for hydric soils.

Hydrophytic vegetation also occurs along the south bank of the slough. These communities occur sparsely (less than 20% areal coverage) in areas of exposed sediments along the lower portion of the bank during the middle to late part of the growing season and after surface water levels have dropped. Dominant species are flatsedge, false pimpernel, love grass, cottonwood seedlings, and purple ammannia. Areas higher on the bank are vegetated variously between 20% (on steeper slopes) and 100%. Common species within these communities include beggars ticks, love grass, box elder, silver maple, black willow seedlings, green ash, pigweed, flatsedge, and morning glory.

Little Femme Osage Creek

The Little Femme Osage Creek is identified by the National Wetlands Inventory as a lower perennial riverine wetland with an intermittently exposed, unconsolidated bottom. Temporarily flooded palustrine forested wetlands occur sporadically along portions of the creek. North of the Katy Trail, the creek area supports a variety of forested and herbaceous vegetation communities that are dominated by hydrophytic species such as clearweed, silver maple, box elder, American elm, beggar-ticks, smartweed, lady's thumb, wood nettle, and white grass.

The banks of the Little Femme Osage Creek south of the Katy Trail are sparsely vegetated and lack a well developed floodplain. A dike extends along the east side of the creek. A portion of the creek is identified in the National Wetlands Inventory as a temporarily flooded, palustrine forested wetland, and scrub-shrub wetland. Common species in vegetated areas along the banks include dogbane, sandbar willow, pigweed, flatsedge, blue vervain, and beggars ticks. This portion of the creek has been rerouted to form a new confluence with the Femme Osage Creek.

Femme Osage Creek

The Femme Osage Creek, downstream of the confluence with the Little Femme Osage Creek, has been rerouted to form a new confluence with the Missouri River. The channel is steep sided and bordered on each side with dikes. The creek is classified by the National Wetlands Inventory as a lower perennial riverine wetland with a permanently flooded unconsolidated bottom. A narrow band along the right side of the channel is identified as a temporarily flooded palustrine emergent wetland. The creek lacks a well developed floodplain, although forested areas to the north of the creek occasionally retain overbank floodwaters and support hydrophytic species such as silver maple, box elder, beggars ticks, false nettle, arrow head, and buttercup.

5.5 Significant Observations

The ecological investigations indicate that there are no adverse impacts to biological communities in the vicinity of the quarry. This conclusion is based on the following:

- Survey data indicate no significant differences in species diversity and community equality between study areas and reference areas for trees and saplings/shrubs.

- Communities south of the quarry are typical of Missouri floodplain habitat.

- Fish surveys conducted at the Femme Osage Slough and Little Femme Osage Creek show a diverse and typical fauna is present.

- Herpetofauna survey results indicate no significant differences between numbers and types of species observed at the quarry and the reference location.

- No State or Federal listed species were found during herpetofauna and vegetation surveys. Federal threatened bald eagles were observed during winter surveys in the area between the quarry and the Missouri River.

- Potential wetland areas exist in the quarry residual area and will require further delineation if remedial action is taken in these areas.

6 SOIL INVESTIGATIONS

This section summarizes the results of soil investigations performed to establish background levels for site related contaminants in soils and to evaluate the vertical and horizontal extent of soil contamination, both inside and outside the quarry. A lithologic description of the units of interest is also presented, with an emphasis on factors that could affect groundwater movement. Contamination of soil and bedrock in the quarry proper is discussed separately from areas outside the quarry because these areas are composed of different soil types and were contaminated by separate processes.

6.1 Previous Investigations

In 1979, Lawrence Berkeley Laboratory sampled soil along the rim of the quarry and north and south of the slough (Ref. 27). In 1984, Oak Ridge Associated Universities performed soil sampling to a depth of 3 ft to determine the extent and magnitude of radionuclide contamination along the perimeter fence at the quarry and in the area of the Femme Osage Slough (Ref. 28). In addition, United Nuclear Corporation collected samples from the surface to the top of bedrock north and south of the slough (Ref. 29). Information derived from these studies formed the basis for the quarry residuals investigations.

6.2 Quarry Proper

6.2.1 Soil and Rock

Unconsolidated soils in the quarry area include glacially derived loess; residual soil formed by weathering of the bedrock (residuum); and sediment deposited by the Missouri River and its tributaries (alluvium).

Loess, a silty clay soil developed from wind-blown materials deposited during and following the Wisconsin glaciation (Ref. 30), is present in upland areas including the rim of the quarry. Borehole logs indicate that the loess deposits in the vicinity of the quarry are from 15 ft to 30 ft thick and are likely composed of the Peoria Loess and Roxana Silt. These loess deposits are not saturated in the vicinity of the quarry.

Residuum, a stiff clay with chert and limestone fragments, is the product of weathering of the underlying limestone and is present on the bluff and in areas north of the quarry. Based on geologic logs, the residuum ranges from 3 ft to 18 ft thick and is not saturated in the vicinity of the quarry.

Native soils (loess and residuum) adjacent to the rim of the quarry were disturbed during mining of the quarry and waste disposal activities. Undisturbed soils (i.e., soils that were not moved from their natural location) may underlie disturbed soils, but in some areas, disturbed soils comprise the entire surface-to-bedrock interval. The soil cover along the quarry rim and on an isolated limestone knoll inside the quarry is up to 30 ft thick. Near-vertical fractures intersecting the Kimmswick-Limestone walls and benches of the quarry are also filled with disturbed and undisturbed soils.

Soil, gravel, and sediment from surface water runoff and remediation activities have accumulated in floor fractures and depressions and in the lowest portion of the quarry, referred to as the "sump." Floor depressions are broad features greater than 2 ft deep. Sediment thicknesses in the floor depressions and in the "sump" range from less than 1 in. to approximately 18 in., but are typically less than 3 in. in depth.

Floor fractures in bedrock units are restricted to the Kimmswick Limestone benches (the 484 ft bench and the 500 ft bench) and are generally less than 0.5 ft wide, with a few exceeding 2 ft. The trend, frequency, and aperture of quarry fractures are discussed in detail in Section 8. The volume of soil, sediment, and rock material in fractures and depressions is minor compared to the total volume of rock and soil present in the quarry.

6.2.2 Remedial Investigations - Quarry Proper

Soil was sampled at locations within the quarry proper and at two background locations as shown on Figure 6-1 and as detailed in Table E-1 of Appendix E. Some soil samples were taken prior to completion of the bulk waste removal in areas that would eventually be inaccessible. Sampling was designed to meet the following objectives:

1. Identify contamination in disturbed soils, fracture soils, and sump soils (residuals) remaining after bulk waste removal. Because the performance criteria for bulk waste removal were based on visual observation, screening guidelines were established to guide additional removal processes (Ref. 2). Samples were collected on 30 ft (or smaller) grids from the surface to 5 ft, with additional random samples collected to a depth of 3 ft. After excavation of soils which failed the screening guidelines, newly exposed surfaces were resampled for parameters that prompted removal action.

2. Characterize contaminant levels in residual soils after the bulk waste removal was completed.

Samples were analyzed for radionuclides, nitroaromatic compounds (1,3,5-trinitrobenzene; 1,3-dinitrobenzene; 2,4,6-trinitrotoluene; 2,4-dinitrotoluene; 2,6-dinitrotoluene; and nitrobenzene), metals, polynuclear aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs).

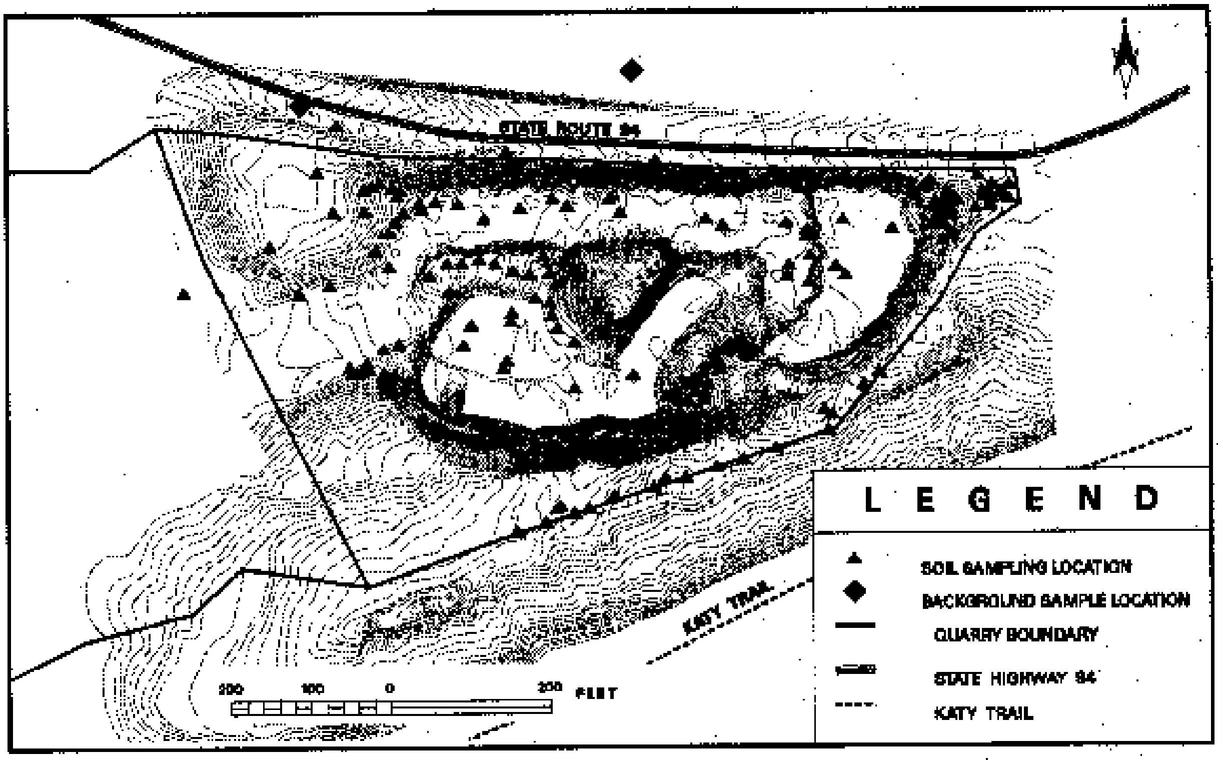

FIGURE 6-1 Soil in Quarry Proper: Sampling Locations

In addition to soil sampling in the quarry proper, rock comprising the inner quarry walls was also investigated for radionuclide contamination. Other contaminants were not investigated because only radionuclides were found at significantly elevated levels in quarry soil. Gamma detectors (NaI and Geiger-Mueller) were used to measure radiological contamination on rock surfaces. As stated in the sampling plan, the bottom 6 ft of the quarry walls was assumed to be the critical area for contamination because this area was in direct contact with the bulk waste. In addition to gamma measurements of rock surfaces, a pressurized ion chamber (PIC) detector was used to measure the dose from ambient gamma radiation at 16 locations in the quarry.

6.2.3 Nature and Extent of Soil Contamination in the Quarry Proper

Sample locations inside the quarry proper, including background locations, are shown on Figure 6-1 and are detailed in Table E-1 of Appendix E. Background samples were analyzed for radiochemical and geochemical parameters and metals (Table H-5, Appendix H). Data on soil in the quarry proper are divided into three groups based on location characteristics. These groups are:

- Soil — Loose soils mantling rim and slopes.
- Fractures — Soils and sediments in wall and floor fractures.
- Sump — Sediments on ramp and floor of sump.

6.2.3.1 Soils. Laboratory results from soil sampling in the quarry proper are summarized in Appendix E (Tables E-2 through E-5). The soil data sets contain results from undisturbed soils and remediated surfaces within the quarry proper. For naturally occurring parameters, the upper 95% confidence limit about the mean for the sample group ($UCL95_s$) was compared to the upper 95% confidence limit about the means for derived background ($UCL95_b$), as described in Section 3. This comparison is illustrated in Figure 6-2A. Maximum values for nitroaromatic compounds are shown in Figure 6-2B. Based on criteria given in Section 3, six metals, six radionuclides, four nitroaromatic compounds, PAHs, and PCBs are identified as potential contaminants.

<u>Disturbed Soils</u>: Disturbed soils on the rim and knoll of the quarry have background or low contaminant levels. As shown in Figure 6-2A, many parameters exceed background, but only selenium, silver, zinc, Ra-226, and Th-230 are present at significantly elevated levels (ratios >2 in Figure 6-2A). None of these contaminants exceed the screening guidelines given in Section 3 (Ref. 6). In comparison to radium and thorium, uranium levels are notably low in disturbed soils.

Elevated soil contaminant levels primarily occurred in the highest part of the quarry on the northeast slope (Figure 6-1). This area was remediated during the last phases of bulk waste removal. Prior to remediation, the northeast slope contained small isolated pockets of concentrated radium- and thorium-rich material interspersed with disturbed native soil. The random, discrete distribution of these materials, location in the highest part of the quarry, and the characteristic insolubility of radium and thorium in the pH range of quarry soils indicate that contamination in this area resulted from primary deposition of waste material, not mobilization and redeposition.

Characterization of soils along the north and east face of the quarry rim was not completed due to access problems. Although samples collected from the top of the north rim did not show contamination, elevated levels were discovered near an area called the "triangle" (Figure 6-1). The remains of a buried drum containing Ra-226 wastes were discovered and removed near this area, but elevated radiation detector readings indicate that additional contamination may still be present. This area cannot be safely accessed to continue characterization. Plans are being prepared to provide safe access for characterization and potential remediation.

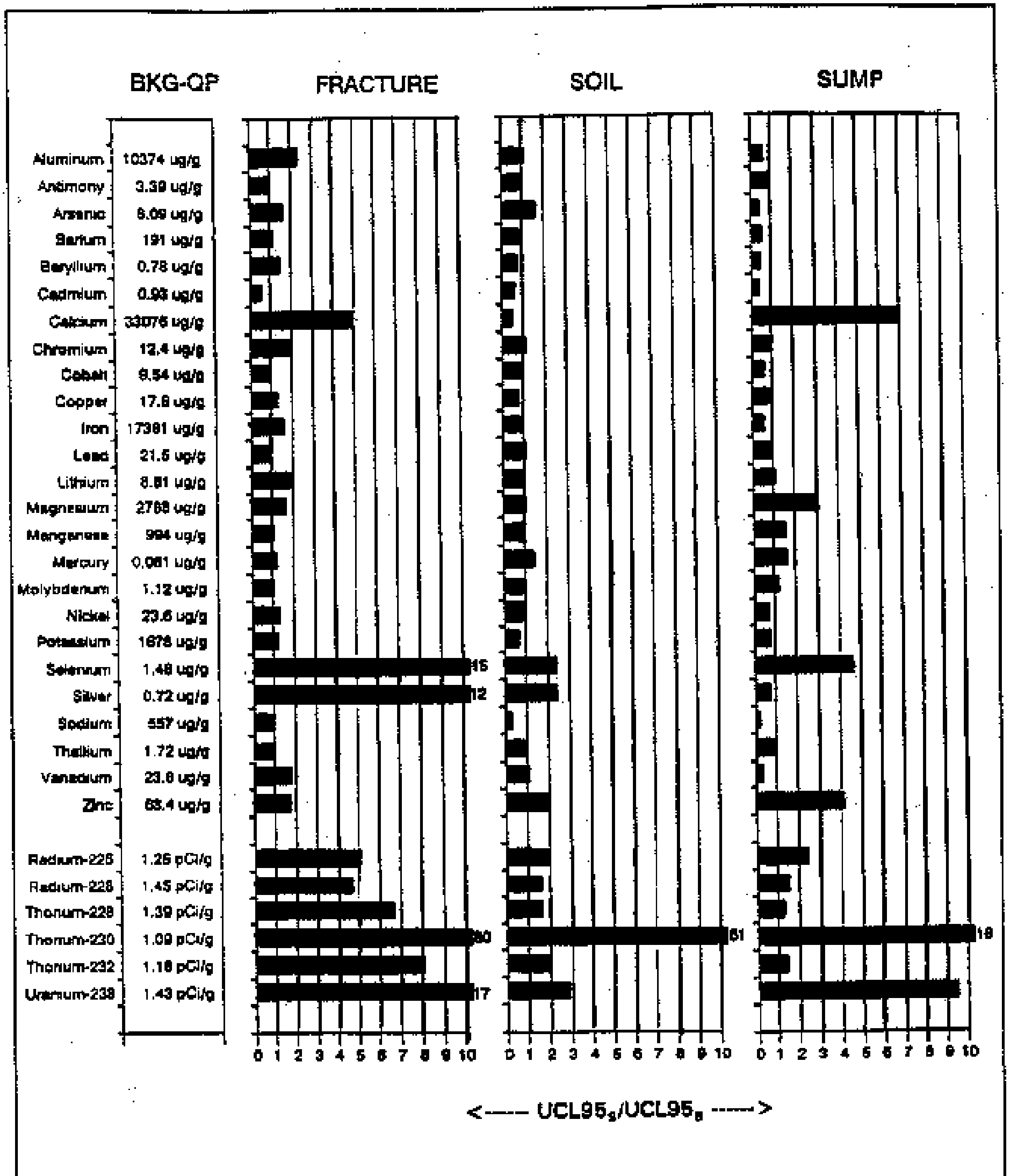

FIGURE 6-2A Soil in Quarry Proper: Background Comparison for Naturally Occurring Parameters

The bar graphs display the UCL95 value for each data group ($UCL95_S$) divided by the UCL95 value for derived background ($UCL95_B$). Values greater than 2 indicate significant deviation from background (Section 3) Note: Ratio set to 1 if 100% of sample data were below the limit of detection.

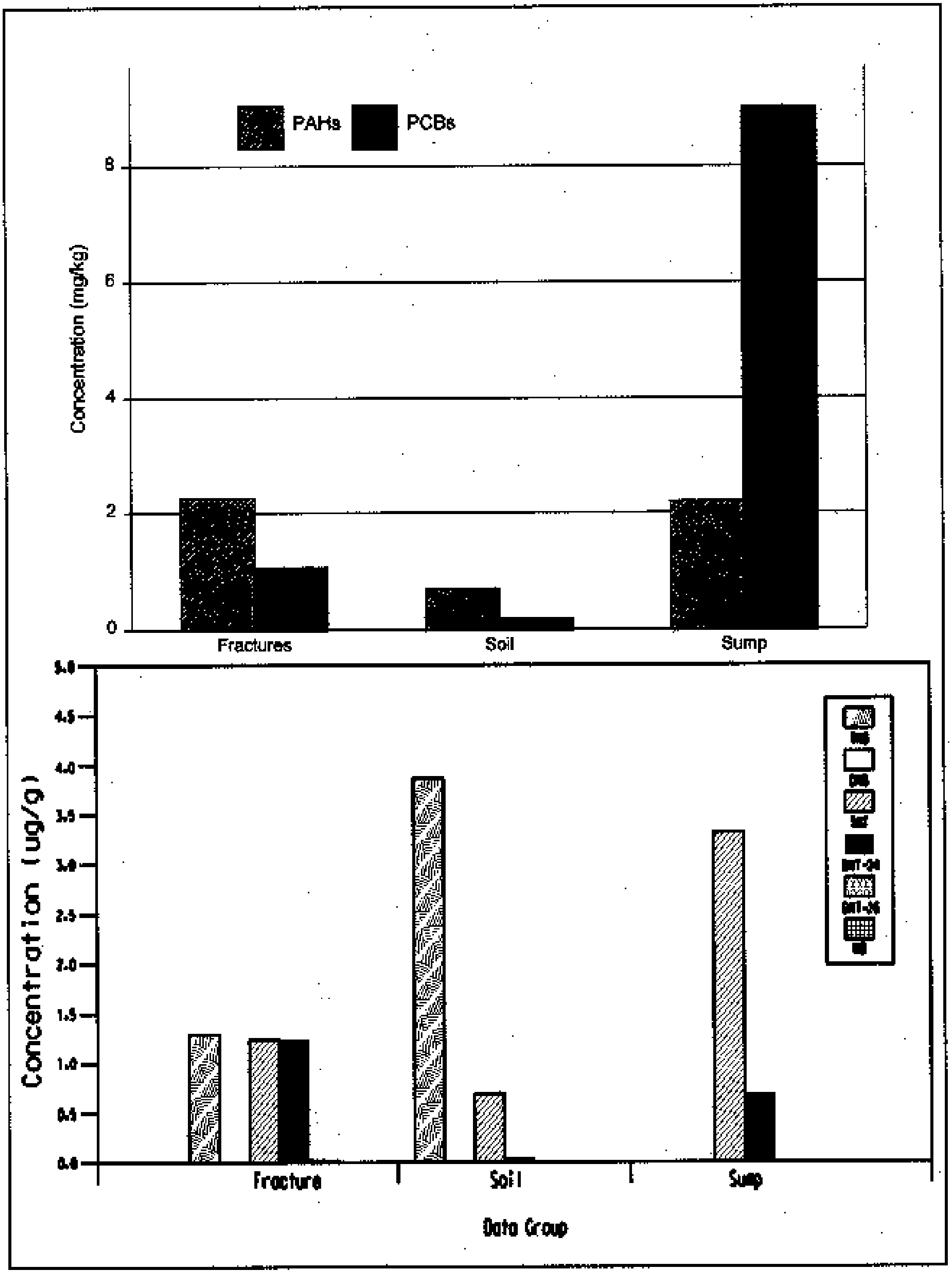

FIGURE 6-2B Soil in Quarry Proper: Maximum Concentrations for PAHs, PCBs, and Nitroaromatic Compounds

The distribution of contaminants in the "triangle" area appears to be similar to that of the northeast slope of the quarry (Figure 6-1). Wide dispersion of the contaminants is not expected. Plans for safely accessing the triangle and the north and east soil faces are being developed. Under current planning, these areas would be sampled and remediated, if necessary, during quarry restoration. A small area of residual contamination in a ditch next to the asphalt pad will also be removed during restoration. These activities will be described in relevant engineering and sampling plans. Results of these actions will be presented in appropriate documents and will also be incorporated into the Quarry Residual Administrative Record.

Fractures: Fractures in the quarry wall contain mostly undisturbed soils and have low levels of contamination. In contrast, fractures and depressions in the quarry floor contain sediments that have been eroded from the rim and higher benches. In some fractures and depressions, fine-grained material containing radium, thorium, and uranium are present. All radium, thorium, and uranium isotopes are significantly elevated with respect to background, but do not exceed the screening guidelines presented in Section 3. Aluminum, selenium, and silver are also elevated in these sediments, but other metals are only slightly above background. None of the metals exceed the screening guidelines. (See Section 3.)

Undisturbed soils are likely present in the deeper portions of fractures intersecting the benches but are not documented for this study. Attempts to sample the deeper portions of these fractures were not successful because sampling devices (augers) encountered rock protrusions and irregularities at relatively shallow depths. Samples of fracture fill were collected from three shallow borings on the 484 ft bench, but the deepest boring extended only 4 ft before encountering rock. Sample results from these borings indicate that elevated concentrations of uranium are present at all levels sampled. Because concentrations do not appear to diminish with depth, uranium-contaminated sediments probably are present deeper in these fractures.

Sump Sediments: Soils in the sump area consist of materials that have eroded from the rim, benches, and fractures of the quarry. Sediment has been transported to the sump during major storms and also during washdown of the quarry in the final stages of bulk waste removal. Much of this material was removed, but a thin layer (< 0.5 ft) remained after bulk waste removal. As in the floor fractures, the major contaminants in the sump are radionuclides (Ra-226, Th-230, and U-238). However, only Ra-226 exceeds the screening guidelines. Low levels of PAHs were detected in some samples. Plausible sources of these contaminants are surface water runoff from nearby asphalt areas used for equipment access and lubricants from equipment operating in the quarry.

6.2.3.2 Rock Surfaces. Results from radiological surveys of the quarry rock surfaces (benches and walls) performed from January to May 1996 are shown in Figure 6-3. With one exception along the north wall, survey readings were at background, indicating that the bulk

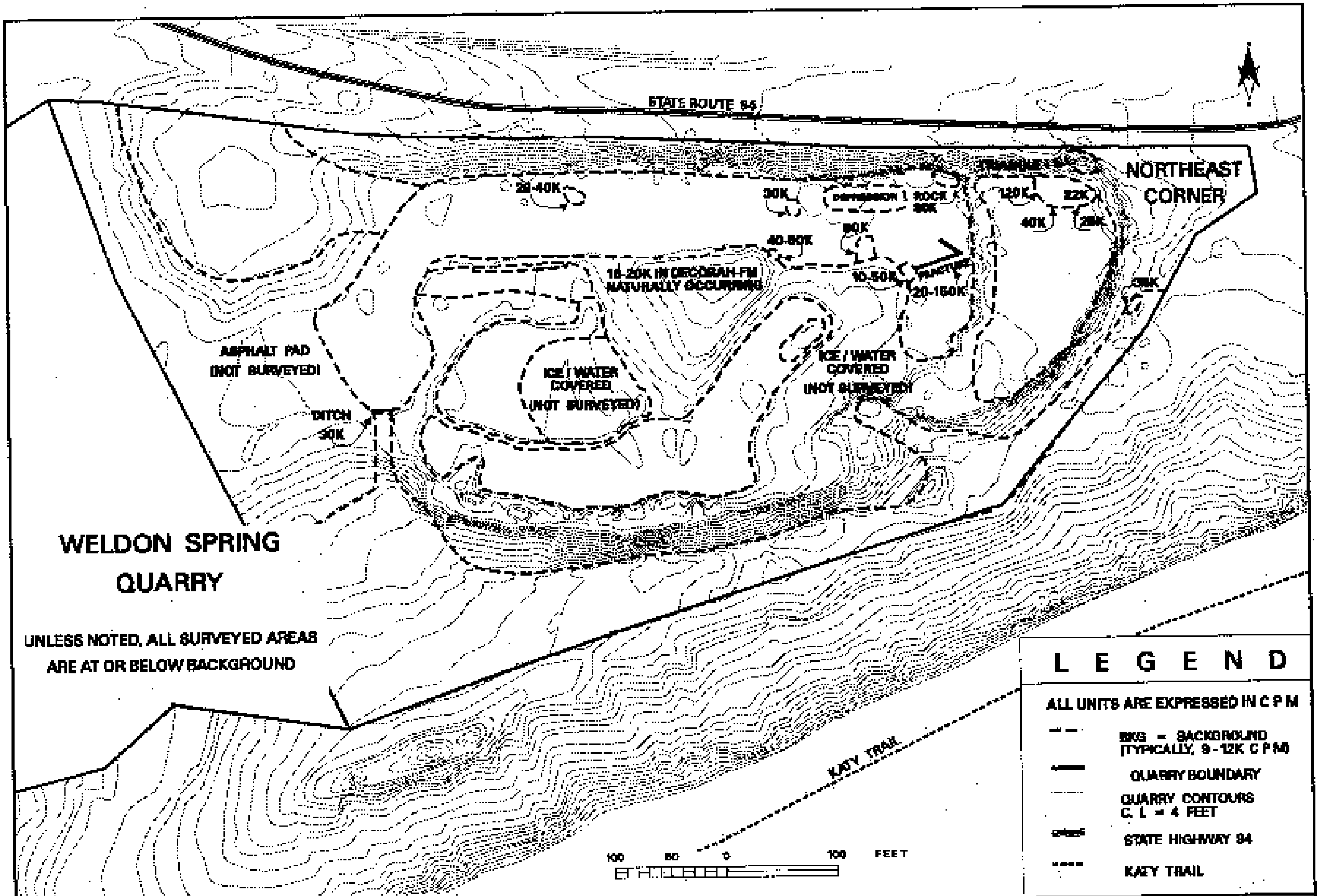

FIGURE 6-3 Sodium Iodide Detector Surveys of Rock Surfaces and Floor Sediments Within the Quarry Proper

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waste had not contaminated the bedrock. A small area of contamination was detected below the 500 ft bench where a rusting drum containing radiological wastes lay against the northeast wall. Prior to bulk waste removal, the rusting of this drum resulted in accumulation of iron hydroxides, which readily sorb metals such as uranium, radium, and thorium, on the quarry wall.

Other elevated survey readings (Figure 6-3) occurred in floor fractures or depressions where sediment and fine particles of waste materials, especially yellow cake, have accumulated. These materials may be residual from the waste storage period or may have collected in these areas during wash-down activities and subsequent rainfalls.

Results from the PIC measurements are shown in Figure 6-4 performed during May 1996. Gamma radiation dose rates were measured 1 m above the floor of the quarry at several locations as designated on the map. Most of these measurements were made using a Reuter-Stokes Environmental PIC. Later, a portable gamma-ray scintillation detector with the response calibrated in micro-Roentgens per hour (μR/hr) against a sealed Ra-226 source was substituted and provided equivalent readings. The portable instrument was preferred because it was easier to handle, and instrument response checks were easier.

6.3 Outside the Quarry Proper

6.3.1 Soil Materials

Alluvial sediments are present in the valleys along the Missouri River, the Femme Osage Creek, and the Little Femme Osage Creek. Differences in composition and grain size are dependent upon depositional history and parent material. Up to 120 ft of alluvium was deposited in the Missouri River floodplain and is divided into a fine-grained unit and a coarse-grained unit.

Fine-grained alluvium was deposited primarily during floods associated with the Missouri River, the Femme Osage Creek, and the Little Femme Osage Creek. These sediments have accumulated in overbank and backwater areas throughout the floodplain. Fine-grained deposits comprise the upper 15 ft to 25 ft of the Missouri River floodplain and consist of silty clay and clayey silt with organic matter and some fine sand. The coarse-grained alluvium consists of fine- to medium-grained sands with some silt grading to coarse-grained sand, cobbles, and boulders with depth. Approximately 20 ft to 80 ft of coarse-grained alluvium is present at the base of the floodplain.

Near the quarry, fine-grained deposits also comprise the full section of the alluvium associated with the Little Femme Osage Creek. These deposits are reworked glacial tills eroded from upland areas north of the quarry and consist of silty clay and clayey silt with alternating layers of fine sand, sandy silt, sandy clay, and stiff clay with gravel.

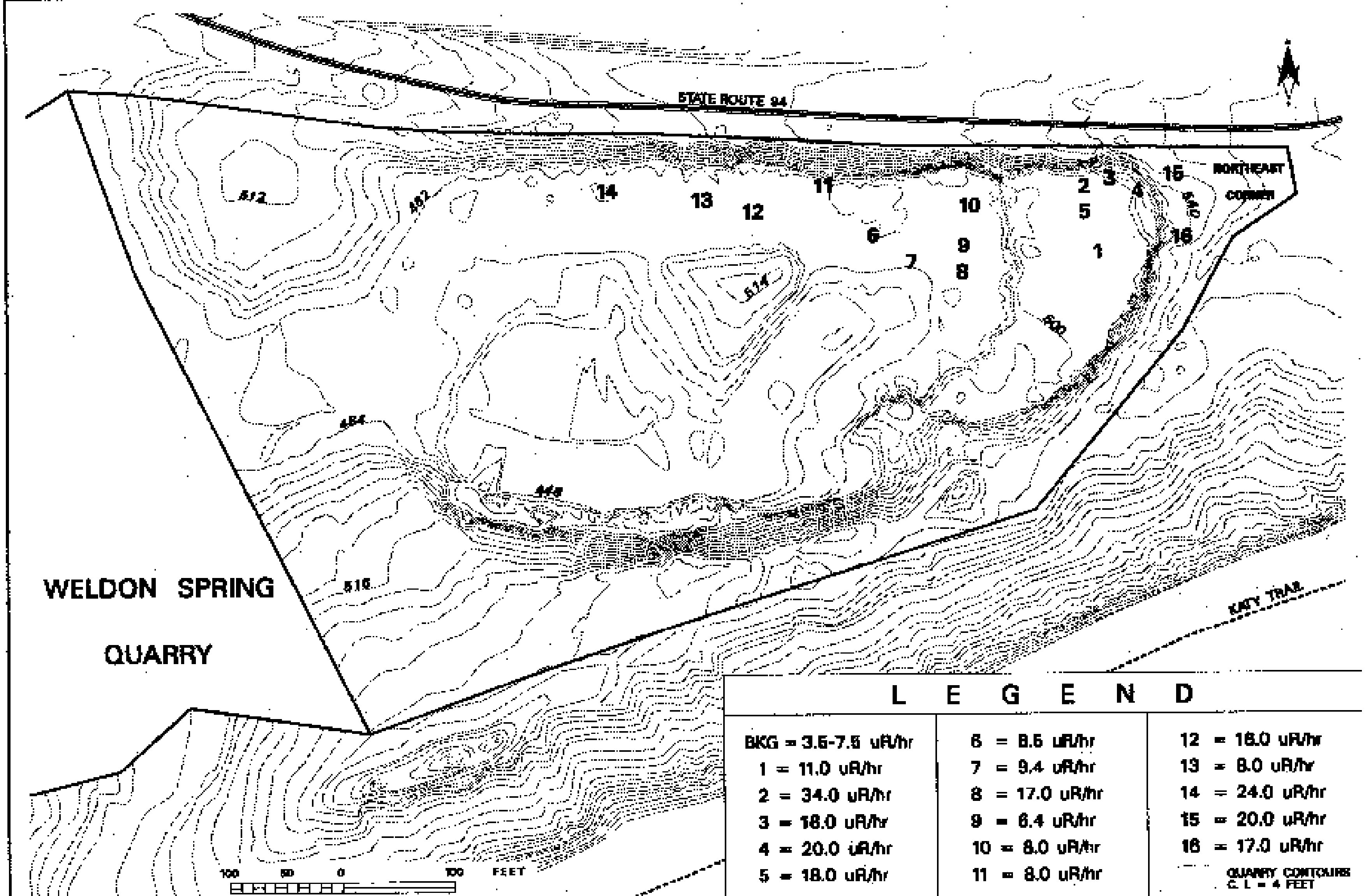

FIGURE 6-4 PIC Dose Measurements for the Quarry Proper

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6.3.2 Remedial Investigations - Outside the Quarry Proper

Surface and subsurface soils were collected outside the quarry to characterize the horizontal and vertical extent of contamination. Sampling focused on the area south of the quarry, especially between the Katy Trail and the Femme Osage Slough. This area included Vicinity Property 9, which was remediated in 1996 under the Chemical Plant Record of Decision (Ref. 9).

During an initial study in support of this remedial investigation (Ref. 31), surface samples (0 ft to 0.5 ft) were collected from 14 sampling units in the area between the Katy Trail and the slough (Figure 6-5). A composite sample was prepared from nine random samples obtained from each of these units. The composites were analyzed for radionuclides, sulfate, metals, and nitroaromatic compounds (1,3,5-TNB; 1,3-DNB; 2,4,6-TNT; 2,4-DNT; 2,6-DNT; and nitrobenzene).

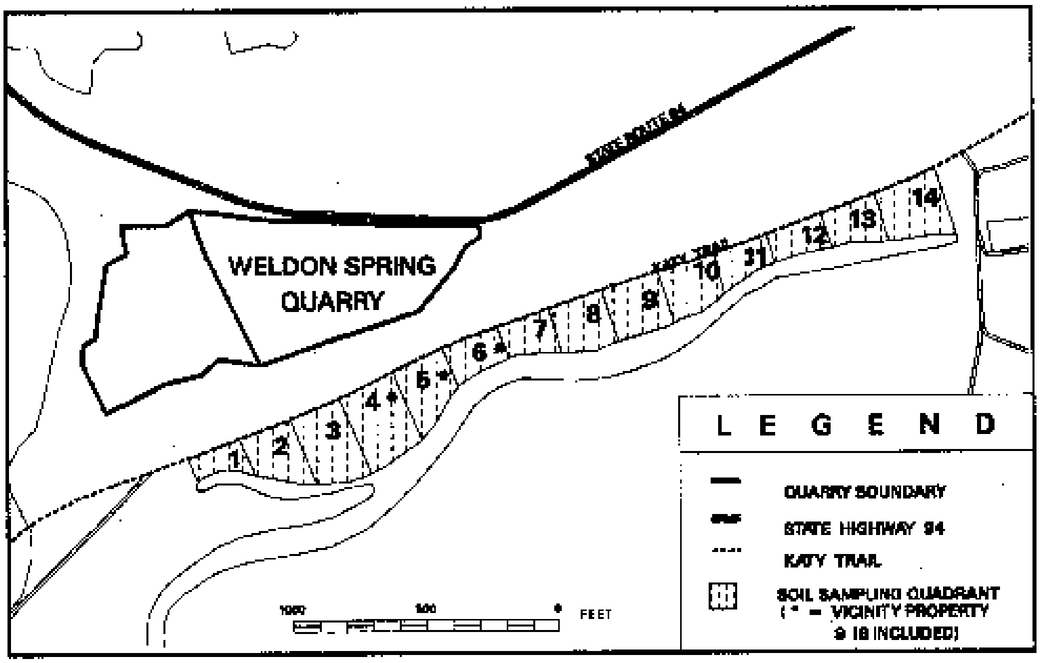

FIGURE 6-5 Soil Outside the Quarry Proper: Surface Sampling Locations

In a second investigation, surface and subsurface samples were collected from soil borings taken in the quarry area, the St. Charles County well field, and at three background locations (Figure 6-6). In most cases, these borings extended to bedrock. Sample intervals were 0 ft to 0.5 ft, 0.5 ft to 2 ft, 2 ft to 5 ft, and at 5 ft or 10 ft intervals to bedrock. All samples were analyzed for total uranium and arsenic. Selected samples were analyzed for analytical parameters defined in Table H-5, Appendix H. A summary of the sampling locations, coordinates, and intervals, as well as boring logs, are provided in Table E-6 and Attachment E-1. Data from the upper 2 ft interval for borings 25, 27, and 38 (Group SQ) were not included in data summaries and statistical analyses because these soils were removed during remediation of Vicinity Property 9.

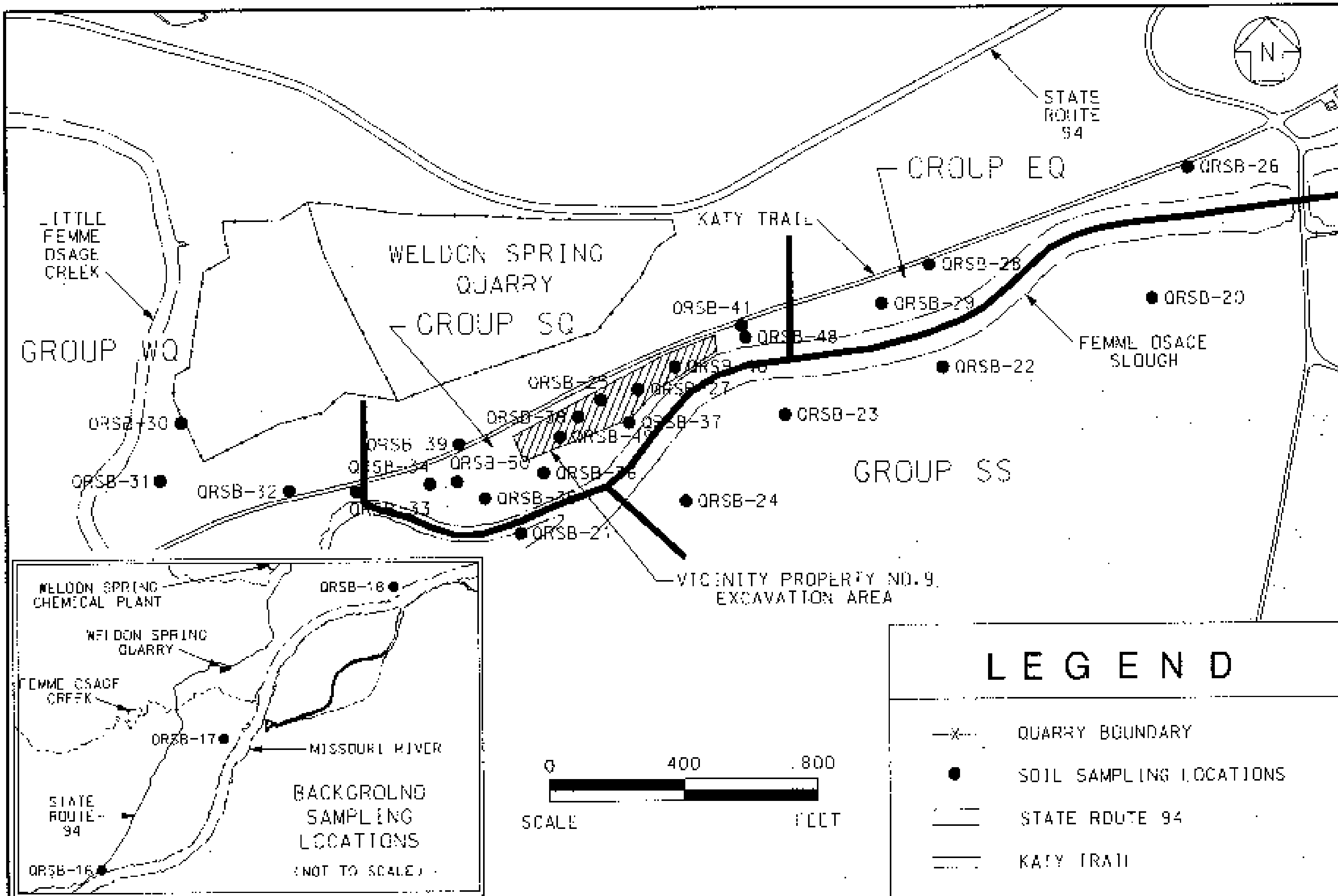

FIGURE 6-6 Soil Outside the Quarry Proper: Background and Subsurface Sampling Locations

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6.3.3 Vicinity Property 9

Vicinity Property 9 (VP 9) was an area between the quarry and the slough and south of the Katy Trail where uranium contaminated soils were identified by investigations performed during the 1980s. The contaminated area was approximately 550 feet long, 200 feet wide, and opposite a bedrock fracture zone described in Section 8. The highest uranium levels were found at depths ranging from 2 to 5 feet below ground surface, and the contamination was attributed to groundwater flow from the quarry (Ref. 28, 29, and 30).

More recently, several borings were advanced to bedrock, and soils were sampled in the VP 9 area as part of this Remedial Investigation. Laboratory results indicate that the highest uranium levels were in the upper 6 inches of the soil profile, which also contained abundant organic material (Table E-7, Appendix E). Elevated uranium levels were identified though the entire length of borings QRSB-25, 27, 38, and 40. In the remainder of the borings in the VP 9 area, uranium contamination was limited to specific intervals which correlated to zones of iron oxide staining or higher contents of organic material. Intervals with a relatively high percentage of sand showed the lowest uranium levels. The VP-9 area was later remediated in January 1996 under the Chemical Plant ROD (Ref.9).

6.3.4 Nature and Extent of Soil Contamination Outside the Quarry Proper

The analytical results from soil samples taken outside the quarry proper were separated into four groups as shown below based on location:

- Group WQ: Soils west of the quarry and north of the slough
- Group EQ: Soils east of the quarry and north of the slough
- Group SQ: Soils south of the quarry and north of the slough
- Group SS: Soils south of the slough

For naturally occurring parameters, the $UL95_S$ for each group was compared to the $UL95_B$, as defined in Section 3. This comparison is shown on Figure 6-7A. Based on the definition in Section 3, four metals, three inorganic anions, three radionuclides, and four nitroaromatic compounds have been identified as potential contaminants (Figure 6-7A). None of these potential contaminants exceed the screening guidelines presented in Section 3. The following discussions focus on these parameters and detected anthropogenic parameters (Figure 6-7B). Data for the sample groups are presented in Tables E-8 through E-10 of Appendix E.

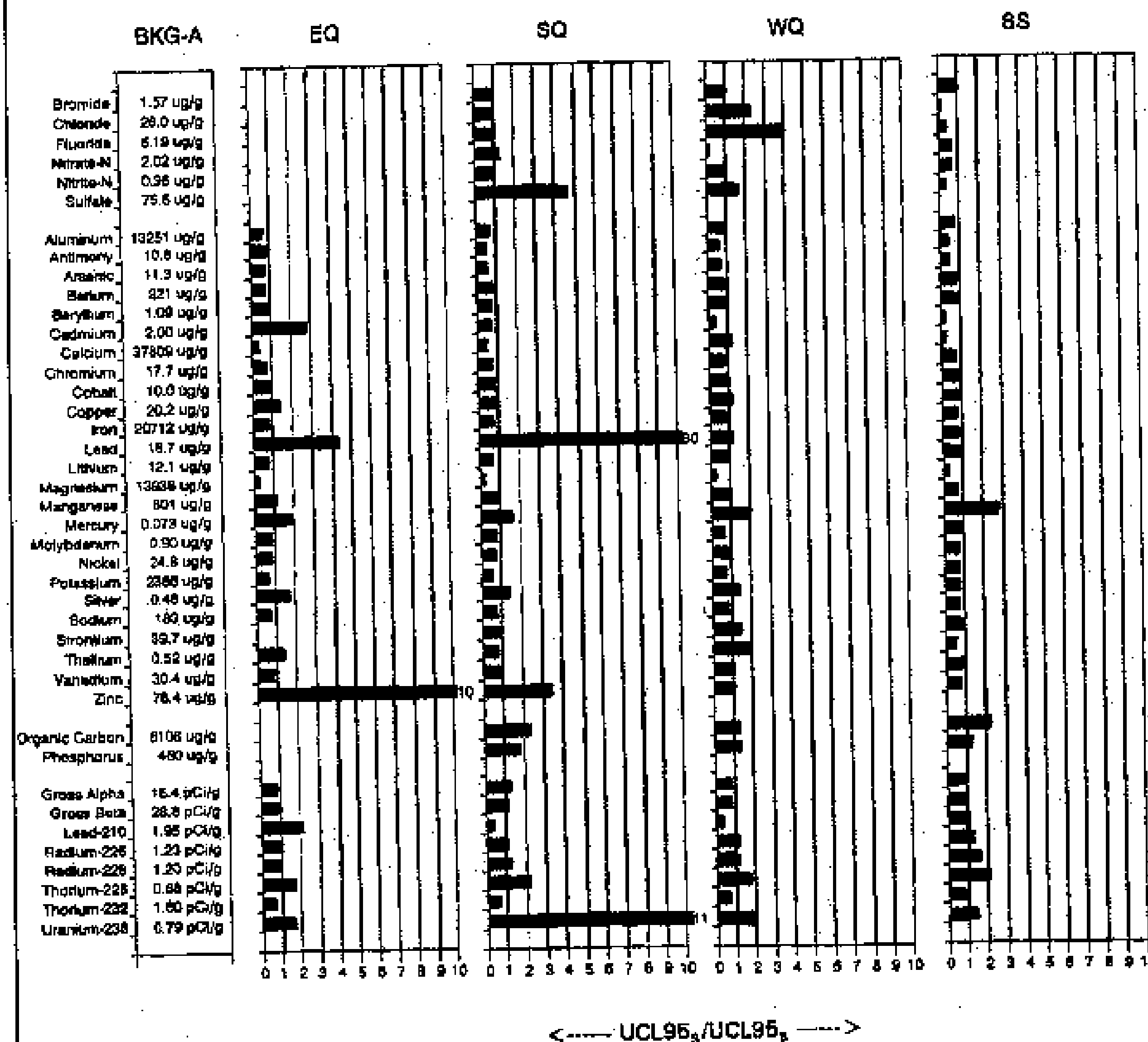

FIGURE 6-7A Soil Outside Quarry Proper: Background Comparison for Naturally Occurring Parameters

The bar graphs display the UCL95 value for each data group ($UCL95_S$) divided by the UCL95 value for derived background ($UCL95_B$). Values greater than 2 indicate significant deviation from background (Section 3) Note: Ratio set to 1 if 100% of sample data were below the limit of detection.

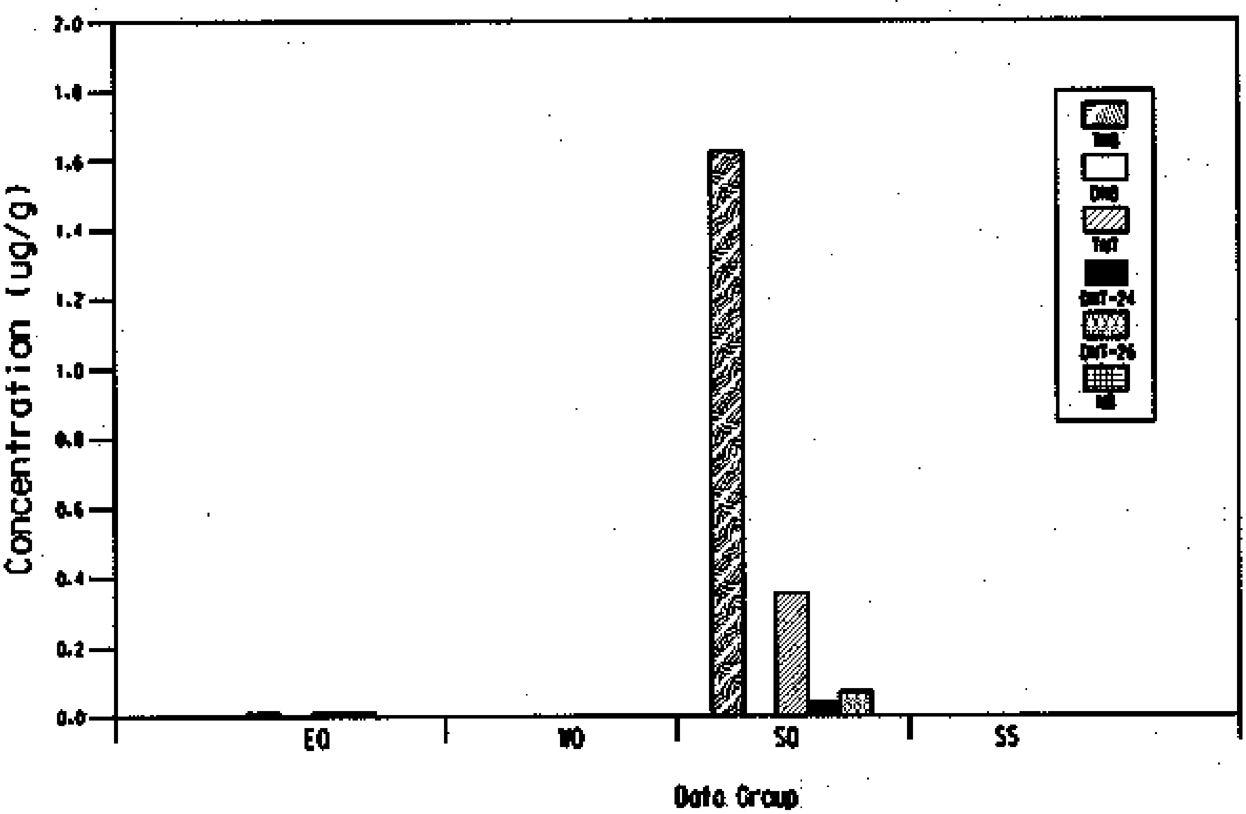

FIGURE 6-7B Soil Outside Quarry Proper: Maximum Nitroaromatic Compound Concentrations

6.3.4.1 Potential Contaminants. Levels of Pb-210, Ra-226, Ra-228, Th-228, and U-238 exceed background in at least one of the four soil groups. With the exception of U-238, Pb-210 (EQ), and Th-228 (SQ and SS), radionuclides are only slightly above background. In general, the highest radionuclide levels occur in soil directly south of the quarry (Group SQ), with the highest U-238 levels occurring near the former Vicinity Property 9 area. In soils east and west of the quarry, elevated U-238 levels generally occur in the 2 ft to 5 ft interval.

Chloride, fluoride, and sulfate significantly exceed background in at least one soil group in the quarry area. Chloride and fluoride levels are above background in soils west of the quarry and sulfate levels are above background in soils south and west of the quarry. The highest values occur in surface samples of soils directly south of the quarry. Elevated sulfate was identified at a depth of 40 ft to 45 ft in boring 31 west of the quarry.

Lead and zinc are the only metals significantly above background, as shown on Figure 6-7A. The highest concentrations of these metals are found south and east of the quarry. Other metals that marginally exceed background are randomly distributed throughout the sample groups. In general, the highest metals concentrations occur in the upper 5 ft of the soil profile.

Low levels of nitroaromatic compounds were detected in soils to the east, west and south of the quarry (groups EQ, WQ and SQ). The highest levels were measured in Group SQ as shown on Figure 6-7B. These compounds were generally detected in the upper 5 ft interval, but were also found in the 10 ft to 20 ft interval at some locations. Nitroaromatic compounds were not detected in soil samples collected from locations south of the slough.

Several pesticides, PCBs, semivolatile compounds, and volatile compounds were detected at low levels at isolated locations. These parameters are identified in Table E-10 of Appendix E. Detections of common laboratory contaminants, such as acetone and methylene chloride, are considered suspect and not representative of soil in the areas sampled.

6.3.4.2 Extent of Contamination Outside the Quarry Proper. Soils contaminated with uranium and nitroaromatic compounds are generally limited to the area directly south of the quarry, which includes the Vicinity Property 9. During excavation of soils in this area, field personnel noted that the highest concentrations of uranium were associated with tree roots and a shallow, dark layer of soil, which was assumed to be rich in organic matter. The apparent association of high uranium levels with organic matter, which readily sorbs uranium (see discussion of Kd values in Section 9), is consistent with the hypothesis that groundwater carrying dissolved uranium was responsible for contamination of Vicinity Property 9. Other observations that support this hypothesis, include:

- Vicinity Property 9 is downgradient of the quarry.
- Elevated levels of uranium are present in groundwater in this area.
- Other relatively insoluble radionuclides, such as thorium and radium, that are associated with uranium are not present at similarly elevated levels in these soils. The absence of these species indicates that spills or discharges of water from the quarry are not likely sources.

Groundwater transport and subsequent sorption of uranium on organic material and iron and manganese oxides or precipitation of solid phases in anaerobic soil zones, may also be responsible for the sporadic occurrences of elevated uranium at deeper levels. Nitroaromatic compounds detected in the upper 5 ft of soil also likely result from groundwater transport and sorption on organic matter. The occurrence of nitroaromatic compounds at deeper intervals may reflect the presence of organic material in these areas, as nitroaromatic compounds are not readily sorbed onto soils (Ref. 59).

The metals and various organic compounds that have been detected at slightly elevated levels in shallow soils south and east of the quarry may have been transported in groundwater from the quarry to these areas. However, groundwater transport from the quarry is not the only plausible source of metals. They could also be derived from flood-related overbank deposits of fine sediment carried by the Missouri River or from runoff from the former Weldon Spring Ordnance Works down the original Little Femme Osage Creek drainage. These sources are discussed in Section 7 as plausible contributors of elevated metals in the Femme Osage Slough and the Little Femme Osage Creek.

6.4 Significant Observations

- Limestone bedrock in the quarry proper does not have fixed contamination.

- Soil in wall fractures within the quarry has background or low levels (less than two times background) of contamination.

- Isolated areas of contamination are present in the "triangle" area and in a ditch south of the asphalt area. Characterization in the "triangle" area will be performed when safe access has been established to this area. These areas are scheduled to be remediated during quarry restoration activities.

- Soil in quarry floor fractures and depressions and at the base of the sump is contaminated with radium, Th-230, and uranium. Other contaminants are either present at low levels or were not detected.

- Low levels of uranium are sorbed onto soils located between the quarry and the slough. Low levels of other contaminants (radionuclides, nitroaromatic compounds, and metals) also occur in this area, primarily in the upper 5 ft interval. Transport of contaminants to this area by groundwater appears to be a plausible explanation for elevated uranium and nitroaromatic levels.

- Overbank flooding by the Missouri River may be a source of elevated metals in surface soils south of the quarry.

7 SURFACE WATER AND SEDIMENT INVESTIGATIONS

This section describes surface water features in the vicinity of the Weldon Spring Quarry and presents data collected to characterize the nature and extent of contamination in surface water and sediments. Plausible sources of contamination for these media are evaluated, and the interaction between surface water and groundwater is examined.

7.1 Physical Description

Precipitation falling in the vicinity of the quarry infiltrates into the subsurface or flows overland to drainages and streams which carry water to the Missouri River. Significant surface water features are shown in Figure 7-1.

Near the quarry, most surface runoff is captured by the Little Femme Osage Creek and the Femme Osage Creek (Ref. 8). Minor runoff also flows into the quarry and collects in the sump area, thus contributing to the quarry pond. The Little Femme Osage Creek, which is immediately west of the quarry, drains upland areas to the north and joins the Femme Osage Creek approximately 2,000 ft southwest of the quarry. Below this confluence, the Femme Osage Creek flows east to the Missouri River, which flows in a northeasterly direction approximately 1 mi to the south of the quarry. Flow gradients in the lower reaches of the Femme Osage Creek and Little Femme Osage Creek are relatively flat. At high water stage, the Missouri River backs up into these creeks causing flow rates to decrease and water levels to rise. During these periods, creek and river water mix, and fine-grained sediments carried by the river may be deposited in the creek channels.

The Femme Osage Slough is an isolated, 1.5 mi long body of water approximately 500 ft south of the quarry. The slough was formed in 1960 when downstream reaches of the Femme Osage Creek and the Little Femme Osage Creek were cut off from their natural channels by a levee constructed by the University of Missouri to prevent flooding of nearby farmland and the St. Charles County well field (Ref. 33). Pre-1960 channels for these streams are shown in Figure 7-2.

Although the floodplain south of the quarry is protected by a levee, flooding is common in this area. Recent flooding of this area occurred in 1993, 1994, and 1995, and typically occurs every 3 to 5 years. The levee system also slows recession of flood waters. After flood events, 1 to 2 months are required to fully drain flood waters from this area (Ref. 8). Water elevations for 100-year and 500-year floods at Missouri River Mile 49 (near the confluence of the Femme Osage Creek and the Missouri River) are 472.8 ft above mean sea level (MSL) and 474.6 ft MSL, respectively (Ref. 8). The 100-year flood elevation on the Femme Osage Creek is 474 ft (Ref. 34).

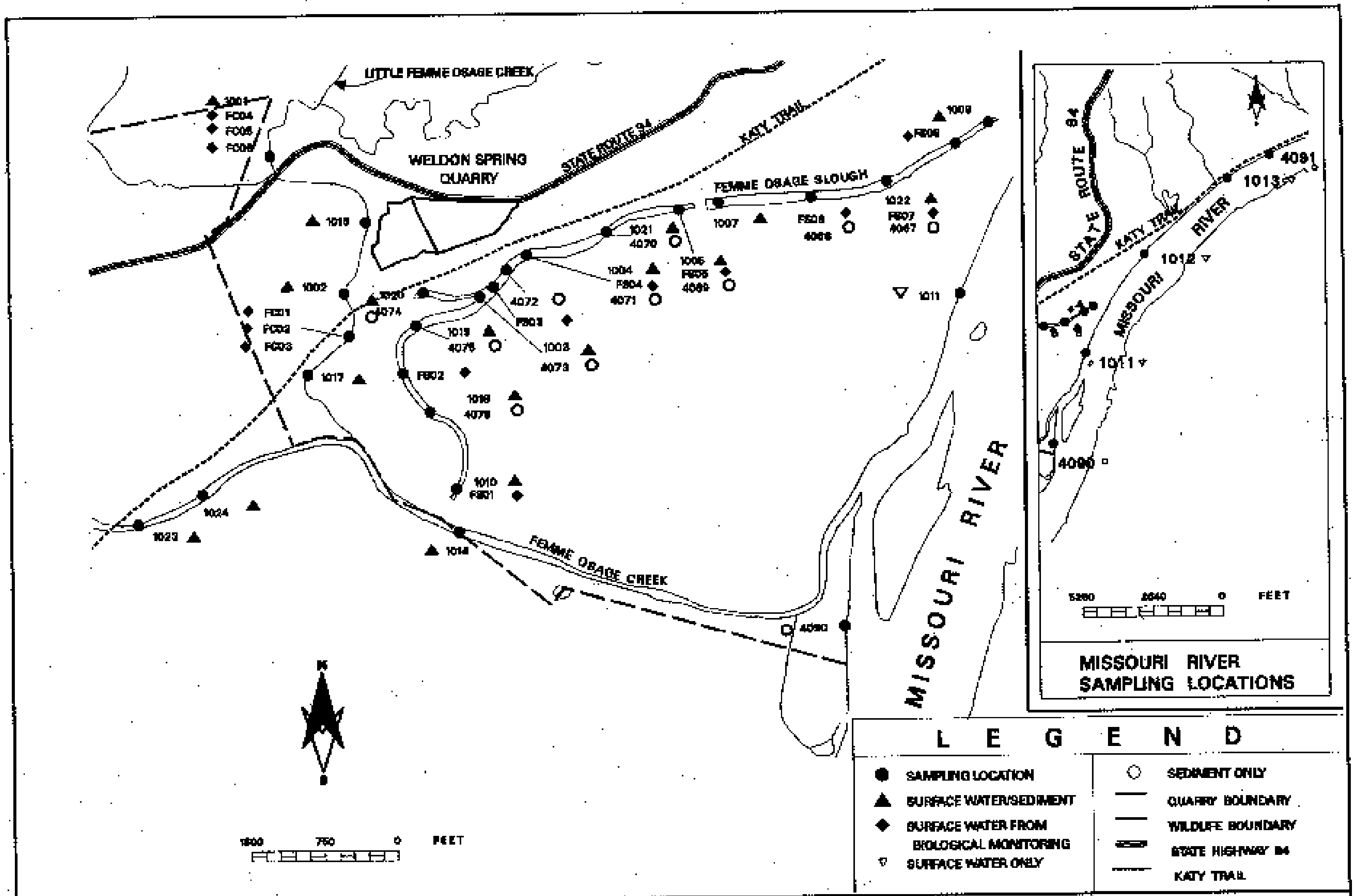

FIGURE 7-1 Surface Water and Sediment: Quarry Area and Missouri River Sampling Locations

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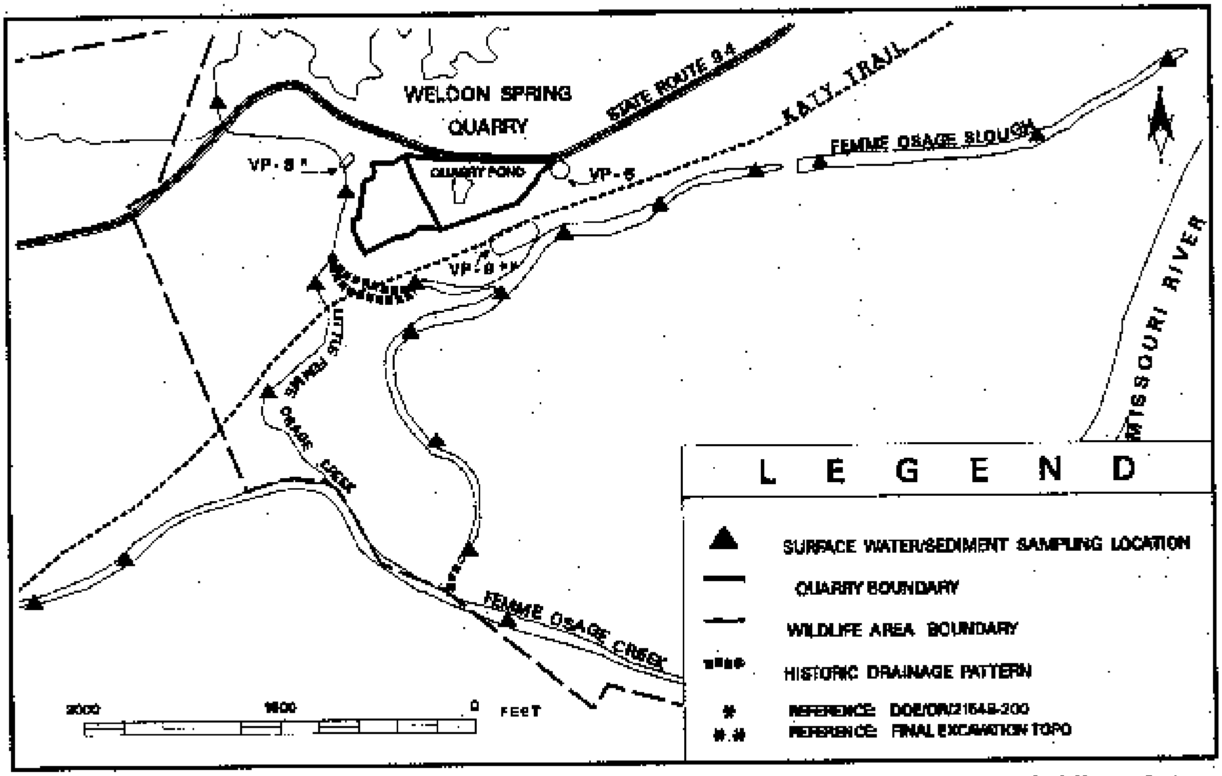

FIGURE 7-2 Femme Osage Creek and Little Femme Osage Creek Historic Drainage Pattern (Prior to 1960)

Sediments in the Femme Osage Creek, the Little Femme Osage Creek, and the Femme Osage Slough primarily consist of fine-grained alluvium derived from erosion and redeposition of upland glacial till soils. These sediments are interlayered with fine river sediments deposited during flood and high water stages of the Missouri River. Based on field observations, the slough and creek sediments range from light brown silty clay to a darker brown silty clay.

7.2 Surface Water and Sediment Investigations

Numerous investigations have been performed to characterize the nature and extent of contaminants in surface water and sediments near the quarry. Studies performed prior to these investigations are summarized in Table F-1 of Appendix F. Surface water data have also been presented in annual environmental monitoring reports (Refs. 35, 36, 37, 38, 39, 40, 41, and 42). Tasks performed to support quarry residuals investigations are described in Appendix F, Table F-2.

7.3 Nature and Extent of Contamination

The results of previous and remedial investigations are summarized in the following sections. For ease of discussion and for statistical analysis, surface water and sediment sampling results are grouped by location. Surface water and sediment data collected as part of special studies conducted in 1988, 1991, 1992, and 1994 (Refs. 43, 44, and 45) are incorporated into the appropriate groups for statistical analysis. The sample groups are:

- CK Little Femme Osage Creek and the downstream portion of Femme Osage Creek (locations 1001, 1002, 1014, 1016, and 1017; special study locations for surface water and sediment FC01-FC06) (Figure 7-1).

- USL Upper Femme Osage Slough (locations 1003, 1004, 1005, 1010, 1018, 1019, 1020, and 1021; special study locations for surface water and sediment: FS01-FS05 and for sediment: 4069-4076) (Figure 7-1).

- LSL Lower Femme Osage Slough (locations 1007, 1009 and 1022; and special study locations for surface water and sediment: FS06-FS08 and sediment: 4067-4068) (Figure 7-1).

- MR Missouri River (surface water locations 1011-1013 and sediment: 4090 and 4091) (Figure 7-1).

- BKG Background (locations 1023 and 1024) (Figure 7-1).

In addition to the locations described above, sediment samples were taken at locations 4067 through 4076 (Figure 7-1). Locations 4067 and 4068 are included in the statistical analysis for group LSL, the lower Femme Osage Slough. Locations 4069 through 4076 are included in the statistical analysis for group USL, the upper Femme Osage Slough. Sediment samples were taken along the Missouri River, 4090 and 4091, and are grouped as MR. The statistical approach and definition of potential contamination applied to sediment data were the same as those applied to surface water data.

7.3.1 Background Characterization

Background data for surface water and sediments were collected from two locations on the Femme Osage Creek (Figure 7-1). The background locations are upstream of the quarry and have not been influenced by the activities at the quarry. During high Missouri River stage, this area has a depositional environment that is similar to the Little Femme Osage Creek and the Femme Osage Slough. Because data have only been collected at these locations since December 1995, the background data sets are quite small. As these data sets are limited, the full range of background variation is probably underestimated, which may lead to calculation of low values for the upper 95% confidence limit about the mean for derived background ($UCL95_B$). Based on criteria presented in Section 3, low values for $UCL95_B$ could increase the number of parameters identified as contaminants in these media.

Locations 1001 and 1016 (Figure 7-1) on the Little Femme Osage Creek are also upgradient of the quarry and were used as background locations in earlier studies. These locations were not used as background for this investigation because the Little Femme Osage Creek continues to receive runoff from the former Weldon Spring Ordnance Works. Locations 1001 and 1016 were grouped with the downstream locations on the Little Femme Osage Creek (CK).

7.3.2 Surface Water Characterization

Surface water samples were analyzed for the parameters shown on Table H-5, Appendix H. Data summaries for samples collected from the Little Femme Osage Creek, the Femme Osage Slough, the Femme Osage Creek, and the Missouri River are shown in Figures 7-3A and 7-3B and presented in Tables F-3 through F-5 of Appendix F.

Data for naturally occurring parameters are compared to background in Figure 7-3A, a series of bar charts that quantify the magnitude by which the upper 95% confidence limit about the mean for the sample group ($UCL95_S$) for each parameter in each group exceeds $UCL95_B$. These graphs show that numerous parameters deviate significantly from background (i.e., have ratios >2) and are considered potential contaminants. Aluminum, manganese, and total uranium also exceed water quality standards in one or more groups. Elevated levels of aluminum and manganese, which are not soluble in the pH-Eh range of surface water in the vicinity of the quarry, probably reflect incorporation of suspended sediment in the samples. Uranium is the primary contaminant in surface water in the vicinity of the quarry. Locations where uranium levels exceed background are shown in Figure 7-4. Nitroaromatic compounds were only detected in the Little Femme Osage Creek; maximum values for these compounds are shown in Figure 7-3B. Herbicides, pesticides, PCBs, and semivolatile and volatile organic compounds were not detected in any surface water samples.

In the CK sample group, 28 naturally occurring parameters exceed background (Figure 7-3A). Of these, four metals (aluminum, chromium, silver, and zinc) and three radiochemical parameters (gross alpha, gross beta, and Ra-226) significantly exceed background (i.e., have ratios >2). Aluminum, antimony, iron, and manganese also exceed water quality standards. Low levels of nitroaromatic compounds were also present in the CK sample group as shown in Figure 7-3B, none of which exceed water quality standards.

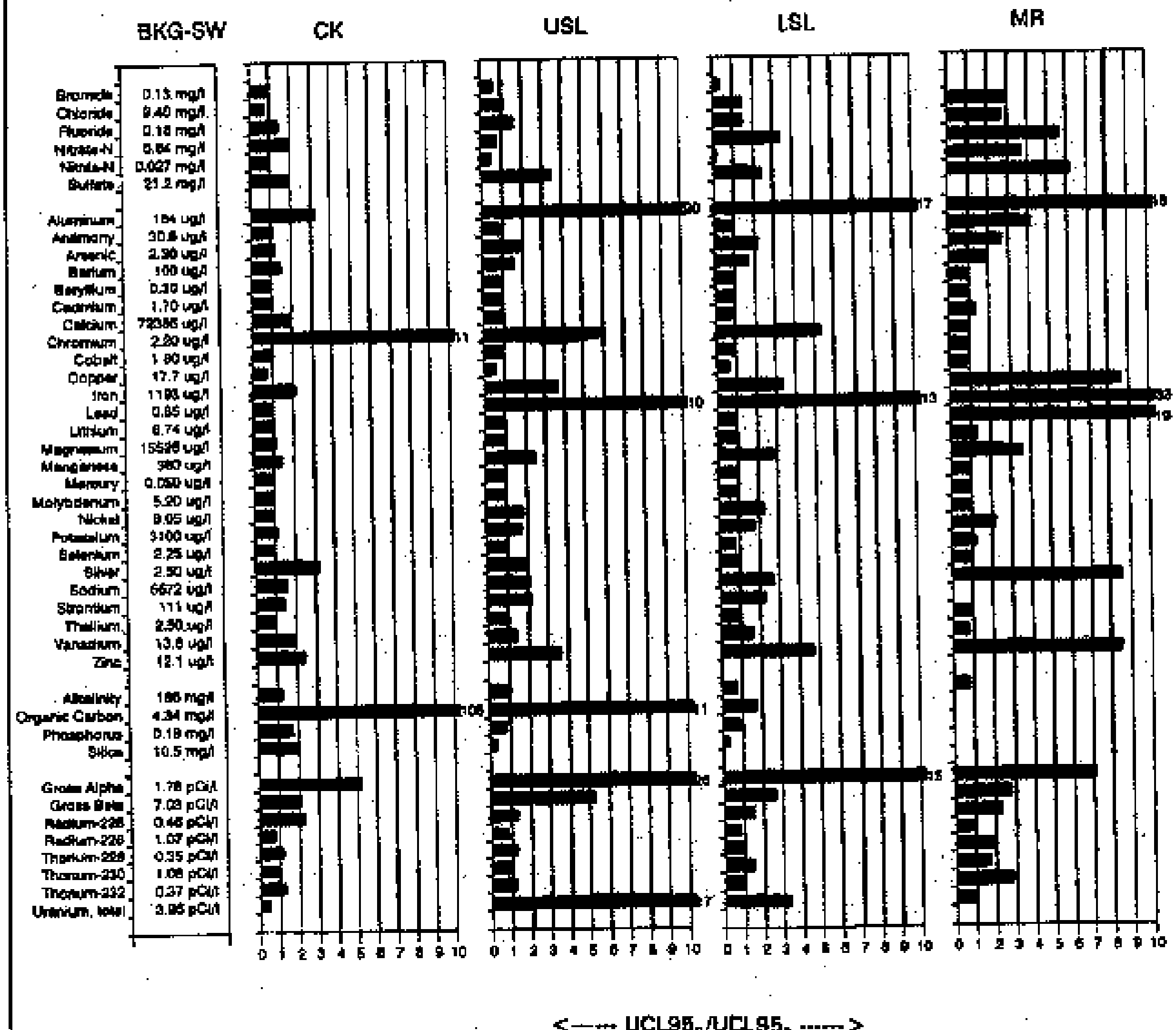

FIGURE 7-3A Surface Water: Background Comparison for Naturally Occurring Parameters

The bar graphs display the UCL95 value for each data group ($UCL95_S$) divided by the UCL95 value for derived background ($UCL95_B$). Values greater than 2 indicate significant deviation from background (Section 3) Note: Ratio set to 1 if 100% of sample data were below the limit of detection.

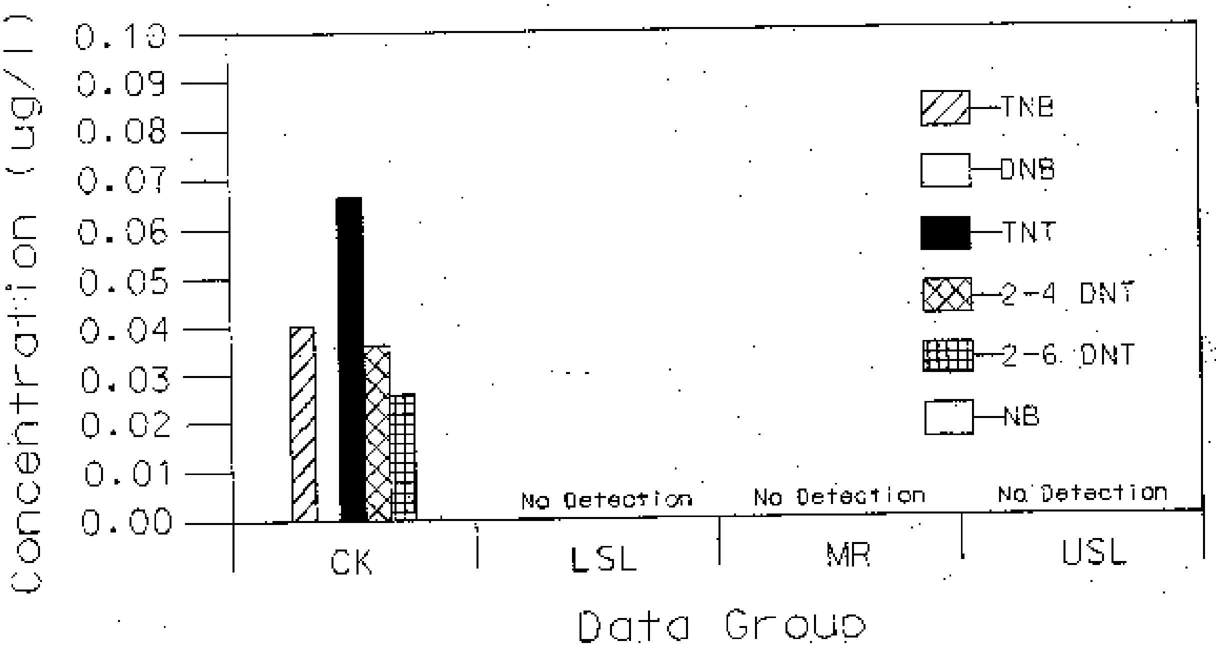

FIGURE 7-3B Surface Water: Maximum Nitroaromatic Compound Concentrations 1990-1996

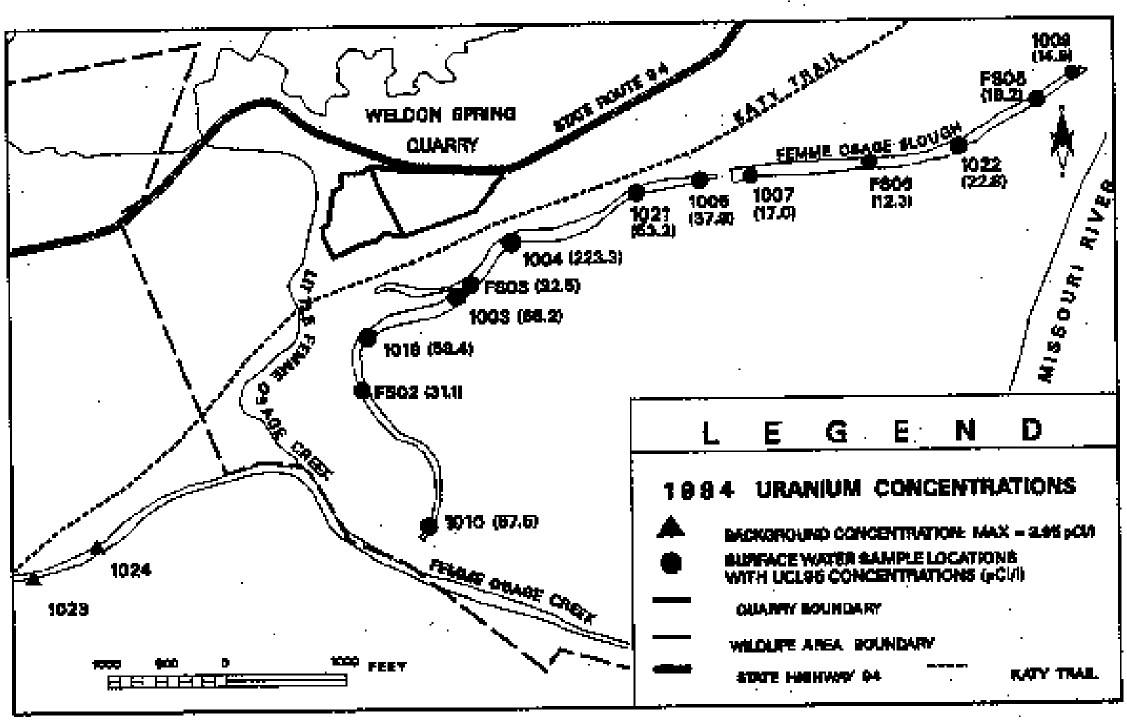

FIGURE 7-4 Surface Water: Locations Where Uranium Exceeded Background During 1994

In the USL sample group (Figure 7-3A), 26 naturally occurring parameters exceeded background. Of these, one anion (sulfate), eight metals (aluminum, chromium, iron, lead, manganese, sodium, strontium, and zinc), and three radiochemical parameters (gross alpha, gross beta, and total uranium) are significantly greater than background (i.e., have ratios >2). Aluminum, antimony, iron, manganese, thallium, gross alpha, and total uranium exceed water quality standards.

In the LSL sample group (Figure 7-3A), 23 parameters exceed background. Of these, two anions (nitrate and sulfate), ten metals (aluminum, arsenic, chromium, iron, lead, manganese, nickel, sodium, strontium, and zinc), and three radionuclides (gross alpha, gross beta and total uranium) significantly exceed background (i.e., have ratios >2). As in the USL group, aluminum, antimony, iron, manganese, thallium, gross alpha, and total uranium exceed water quality standards.

Data for the Missouri River (MR sample group) are also compared to background in Figure 7-3A. Contaminated water from the quarry is a minimal fraction of the Missouri River water budget, but at high water stage the river contributes a significant fraction of the water in the Femme Osage Slough and also contributes to the lower reaches of the Little Femme Osage Creek and the Femme Osage Creek. As shown in Figure 7-3A, 27 parameters in the MR group exceed background. Of these, all five inorganic anions (chloride, fluoride, nitrate, nitrite, and sulfate [bromide was not analyzed]), eleven metals (aluminum, antimony, arsenic, cobalt, iron, lead, lithium, manganese, potassium, sodium, and zinc), and four radiochemical parameters (gross alpha, gross beta, Ra-226 and Th-232) significantly exceed background (i.e., have ratios >2). Aluminum, antimony, iron, lead, manganese, and thallium also exceed water quality standards.

7.3.3 Potential Sources of Surface Water Contamination

The Little Femme Osage Creek may receive contaminated water from several sources. Runoff from the Weldon Spring Ordnance Works production area, which lies upstream of the quarry, is the likely source of nitroaromatic compounds detected in the creek. These compounds were detected at upstream locations that are not impacted by the quarry. Elevated levels of metals may also be derived from this area, but they could also result from migration of contaminated groundwater from the quarry. In addition, overland discharge of contaminated water from the quarry during a U.S. Geological Survey (USGS) study (Ref. 33) or influx of Missouri River water during flooding may have contaminated creek sediments, which continue to release these metals to the stream.

Several plausible sources could contribute contaminants to the Femme Osage Slough. Elevated total uranium levels in both the upper and lower portions of the slough, as shown in

Figure 7-4, may result from groundwater seepage along the north bank of the slough, runoff from the Vicinity Property 9 area prior to remediation, or desorption of uranium from contaminated sediments in the slough. The latter source is difficult to defend because uranium concentrations in slough water do not appear to correlate with concentrations in slough sediments. Elevated metals in the slough may be derived from contaminated groundwater seepage, mixing with Missouri River water, and/or desorption of metals from contaminated sediments. The first two processes are also plausible sources for elevated sulfate levels.

The data indicate that the water from the Missouri River, which is periodically introduced into the slough and backs into the Little Femme Osage Creek, is a possible contributor to the elevated concentrations in both these water bodies. Many of the metals that are elevated in the creek and slough are also elevated in the river.

Thallium and antimony, although not elevated above background, may exceed water quality standards, 2 μg/L and 6 μg/L, respectively. This is due to the detection limits for surface water samples are greater than the MCLs for these parameters. Surface water locations will be sampled and reanalyzed for thallium and antimony using lower detection limits.

7.3.4 Sediment Characterization

Sediment samples were collected at locations identified in Figure 7-1 and were analyzed for the parameters listed on Table H-5, Appendix H. Data summaries are presented in Tables F-6 through F-8 of Appendix F.

Data for naturally occurring parameters are compared to background in Figure 7-5, a series of bar charts that quantify the magnitude by which $UCL95_S$ for each parameter in each group exceeds $UCL95_B$ for background. These graphs show that numerous parameters significantly exceed background (i.e., have ratios >2) and are considered potential contaminants. However, none of these potential contaminants exceed screening guidelines presented in Section 3. Locations where U-238 exceeds background are shown in Figure 7-6. Anthropogenic parameters, including nitroaromatic compounds, were not detected in any sample group.

In the CK sample group, sulfate, four metals (antimony, calcium, magnesium, and strontium), and U-238 significantly exceed background (i.e., have ratios >2). None of these constituents exceeds the screening guidelines presented in Section 3.

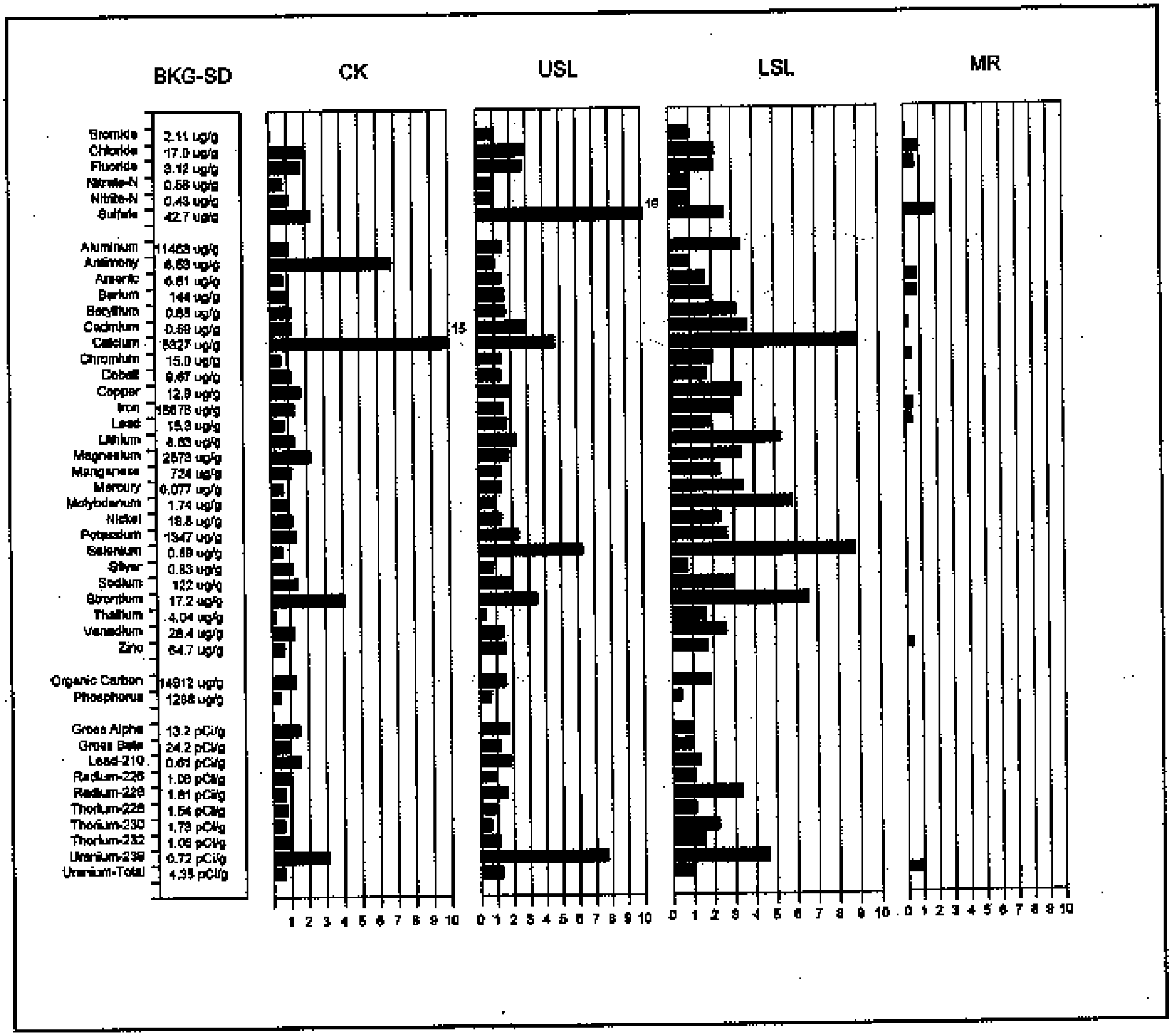

FIGURE 7-5 Sediment: Background Comparison for Naturally Occurring Parameters

The bar graphs display the UCL95 value for each data group ($UCL95_S$) divided by the UCL95 value for derived background ($UCL95_B$). Values greater than 2 indicate significant deviation from background (Section 3) Note: Ratio set to 1 if 100% of sample data were below the limit of detection.

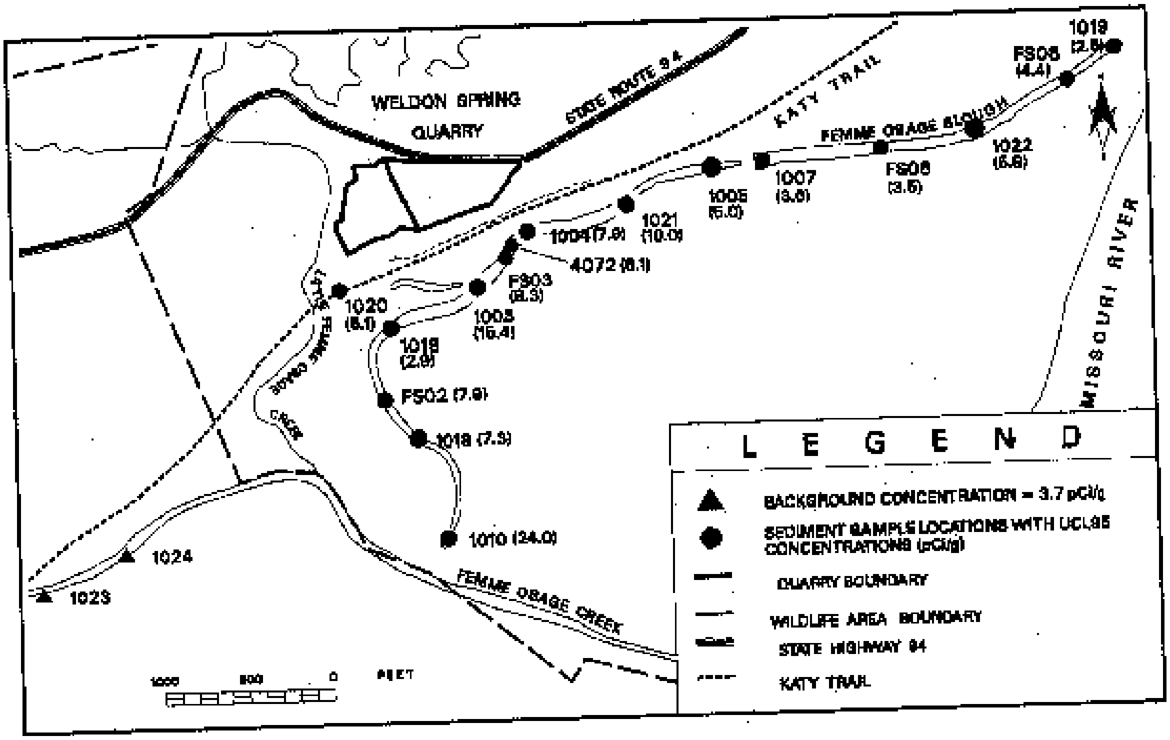

FIGURE 7-6 Locations Where Total Uranium Concentrations Exceeded Sediment Background

In the LSL and USL sample groups, three inorganic anions (chloride, fluoride, and sulfate), 18 metals (aluminum, beryllium, cadmium, calcium, chromium, copper, iron, lithium, magnesium, manganese, mercury, molybdenum, nickel, potassium, selenium, sodium, strontium, and vanadium) and three radionuclides (Ra-228, Th-230, and U-238) significantly exceed background (i.e., have ratios >2). Concentrations of most metals are highest in the LSL group, whereas uranium and sulfate are highest in the USL group as shown in Figure 7-5.

Missouri River sediment samples are generally at or below background levels (Figure 7-5). Sulfate is elevated above background. The locations for the MR sample group were sampled only once (after the 1995 flood) and analysis did not include the entire list of analytes, as indicated in Figure 7-5.

7.3.5 Sources of Sediment Contamination

The elevated metal levels in the CK sample group could result from flood deposition of suspended sediment in Missouri River water; discharge of contaminated quarry pond water during a USGS study (Ref. 33), or wastewater discharge and runoff from the former Weldon Spring Ordnance Works. Most likely, sediment contamination in the Little Femme Osage Creek is the

Ordnance Works. Most likely, sediment contamination in the Little Femme Osage Creek is the result of a combination of these sources. The slightly elevated U-238 levels in these sediments may have resulted from runoff from former Vicinity Property 8 prior to remediation (Figure 7-2). Vicinity Property 8 was located immediately upslope from the quarry and was an isolated area of radiologically contaminated soil.

Sediments in the slough were also probably contaminated by a combination of processes. Prior to 1960, the lower reaches of the creeks that became the Femme Osage Slough were areas that favored settling of suspended fine material from potentially contaminated upstream sources. Metal contamination in the LSL sample group (Figure 7-5), which is closest to the Missouri River inlet valve, likely reflects deposition of colloidal phases and fine-grained sediments carried in suspension by the Missouri River during controlled inflow or flood events. U-238 in the USL sample group, which is closest to the quarry, likely results from quarry-contaminated groundwater seeping into the slough at discrete points along its north bank and runoff from the Vicinity Property 9.

7.4 Groundwater and Surface Water Interaction

7.4.1 Quarry Pond

Although technically a surface water body, the quarry pond is isolated from the surface water system. The quarry pond collects rain water and surface water runoff from the rim and higher levels of the quarry proper. The pond also receives some groundwater discharge along its northern, upgradient, wall and discharges to the groundwater via near horizontal partings near the Kimmswick Limestone/Decorah Group contact along its southern wall.

Prior to bulk waste removal, the quarry pond maintained an elevation of 465 ft MSL, which is approximately 10 ft above the Kimmswick Limestone-Decorah Group contact (see Section 8 for a detailed discussion). During the bulk waste removal action, water was continuously pumped from the pond to the quarry water treatment plant to facilitate the waste removal. At the end of this action in December 1995, approximately 0.5 ft of water and sediments remained on the floor of the sump, which is at an elevation of about 439 ft MSL. In mid-December 1995, the pumping was stopped and the pond was allowed to recharge according to the plan presented in the *Quarry Residual Sampling Plan, Addendum 2: Phase 2 Sampling* (Ref. 2). In March 1996, the pond was pumped down again because uranium levels exceeded the 600 pCi/l criterion set in the recharge study. Natural recharge resumed in mid-April 1996.

The quarry pond was routinely monitored before the start of bulk waste removal. Chemical data from this monitoring were reported in the Weldon Spring annual site environmental reports for 1987 through 1993 (Refs. 35, 36, 37, 38, 39, 40, 41, and 42). The pond was also sampled for metals, inorganic anions, radionuclides, and nitroaromatic compounds in March 1996, before the pond was pumped. Results from this sampling are presented in Appendix F, Table F-9.

Total uranium (1,090 pCi/l) was the only parameter found at significantly elevated levels in the March 1996 sampling event. Trace levels of nitroaromatics and Ra-226 and Ra-228 were also detected (less than 1.0 pCi/l). Since resuming quarry recharge in mid-April 1996, uranium is the only parameter that is routinely monitored. During this period, uranium levels have fluctuated between 400 and 550 pCi/l but have never exceeded the 600 pCi/l criterion. Uranium and precipitation data collected during the recharge period are shown as a function of time in Figure 7-7. This decrease in uranium levels is likely attributed to the remediation of the northeast corner early in 1996. Prior to this, contaminated soils and materials were accessible to precipitation and contributed to the run-off collected in the quarry pond.

7.4.2 United States Geological Survey Groundwater and Surface Water Studies

The USGS conducted a study to identify the interaction between groundwater and surface water systems in the quarry area (Ref. 46). Three staff gages were installed along the Little Femme Osage Creek; four were installed in the Femme Osage Slough; and one was installed in the Missouri River downstream of the slough. In addition, piezometers were installed in the shallow alluvium north and south of the slough. Tables F-10 and F-11 of Appendix F presents water level measurements for each gage and lists the mean daily stage in the slough based on PMC data.

The USGS study concluded that the Femme Osage Slough is a source of gradual recharge to the alluvial aquifer except in extreme flood conditions (Figure 7-8). Analysis of surface water and groundwater levels for this remedial investigation indicates that the alluvial aquifer discharges to the slough along its northern bank at several locations immediately southeast of the quarry. Additional discussions regarding the interaction between the alluvial aquifer and the slough are presented in Section 8.

7.5 Significant Observations

- Total uranium concentrations have been in the 400 pCi/l to 550 pCi/l range since the pond was pumped down in April 1996.
- Surface water and sediments of the Little Femme Osage Creek have been influenced by activities at the former ordnance works.

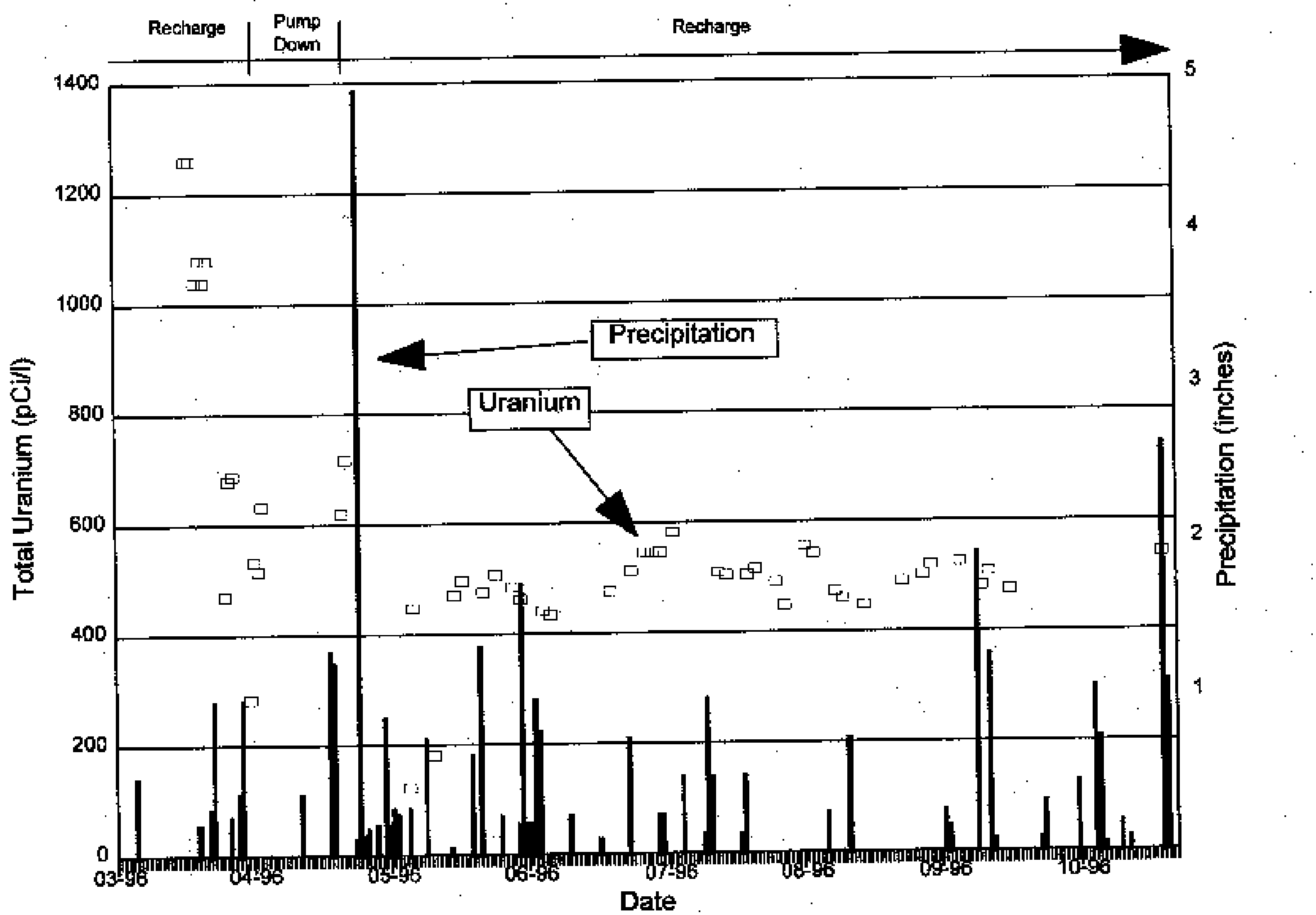

FIGURE 7-7 Surface Water: Quarry Pond Uranium Concentration and Precipitation as a Function of Time

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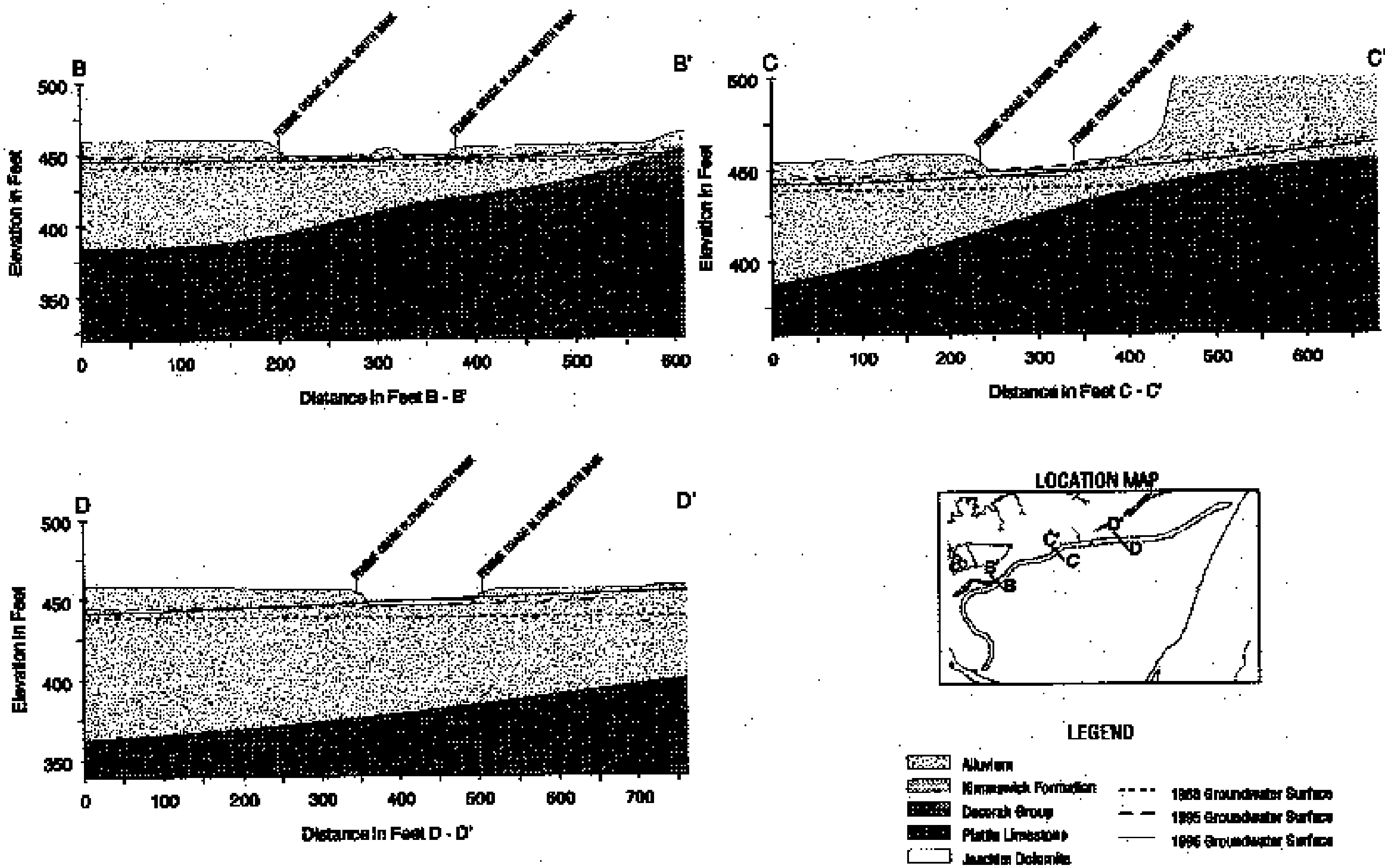

FIGURE 7-8 Cross Sections Showing Relationship of Femme Osage Slough to Groundwater Levels in Alluvium

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- Many of the elevated parameters in the surface water of the upper and lower Femme Osage Slough are also elevated in the Missouri River, which is routinely diverted to, or floods, the slough.

- Surface water and sediments in the Femme Osage Slough have probably been impacted by migration of uranium-contaminated groundwater from the quarry.

- Runoff from the Vicinity Property 9 may have impacted surface water and sediment concentrations in the Femme Osage Slough.

- Uranium, magnesium, and aluminum exceed their respective water quality standards (Table 3-1) in surface water outside the quarry.

- $UCL95_S$ for uranium is 66.5 pCi/l in the upper Femme Osage Slough and 13.3 in the lower Femme Osage Slough.

- Thallium will be re-analyzed in surface water with a detection limit less than or equal to the MCL to determine its presence.

8 HYDROGEOLOGIC INVESTIGATIONS

The results of hydrogeologic studies supporting the Quarry Residuals Remedial Investigation are presented in this section. Historical and recent information pertaining to geology, hydrostratigraphy, and aquifer characteristics of the alluvium and bedrock were evaluated and correlated to develop the site conceptual groundwater model. The model describes the physical framework of the underlying aquifer and potential groundwater pathways for contaminant migration.

8.1 Hydrogeologic Setting

The generalized hydrostratigraphy in the Weldon Spring area is presented on Figure 8-1. Regional aquifers include shallow, middle, and deep bedrock systems and the alluvial system (Ref. 49). Upper and lower confining units are also defined in the regional hydrostratigraphy. The shallow bedrock aquifer system and the upper confining unit shown on Figure 8-1 are not present near the quarry.

8.1.1 Site Geology

Geologic descriptions of the bedrock units and alluvium in the vicinity of the quarry are presented in the following sections. Geologic units are described in descending order.

8.1.1.1 **Alluvium**. The alluvial deposits associated with the Missouri River and its tributaries are discussed in Section 6. In summary, coarse-grained deposits comprise the bottom 20 ft to 80 ft of the Missouri River floodplain. These sediments consist of fine- to medium-grained sand with some silt which grades with depth to coarse-grained sand with cobbles and boulders. Fine-grained deposits comprise the upper 15 ft to 25 ft of the Missouri River floodplain and the full thickness of the Little Femme Osage Creek and the Femme Osage Creek alluvium. These materials were deposited during floods in areas of decreased flow velocity. The fine-grained alluvium consists of silty clay and clayey silt with alternating layers and lenses of fine sand, sandy silt, sandy clay, and stiff clay with gravel. Cross-sections (Figure 8-4 and 8-5) illustrate coarse-grained materials extending into the area north of the slough. In the close vicinity of the quarry, this primarily occurs near well clusters 1013/1014/1031 and 1015/1016/1046. These coarser materials are coincident with bedrock lows which occurs in these areas.

8.1.1.2 **Bedrock**. Bedrock units of interest to this investigation are the Kimmswick Limestone, Decorah Group, Plattin Limestone, and Joachim Dolomite. The quarry was mined through the Kimmswick Limestone and into the upper portion (approximately 15 ft) of the Decorah Group.

SYSTEM	SERIES	STRATIGRAPHIC UNIT	TYPICAL THICKNESS (FT.)(1)	LITHOLOGY	PHYSICAL CHARACTERISTICS	HYDROSTRATIGRAPHIC UNIT
QUATERNARY	HOLOCENE	ALLUVIUM	0 - 120		GRAVELLY, SILTY LOAM.	ALLUVIAL AQUIFER
	PLEISTOCENE	LOESS AND GLACIAL DRIFT (2)	10 - 60	VARIABLE	SILTY CLAY, GRAVELLY CLAY, SILTY LOAM, OR LOAM OVER RESIDUUM FROM WEATHERED BEDROCK.	UNSATURATED (2)
MISSISSIPPIAN	MERAMECIAN	SALEM FORMATION (3)	0 - 15		LIMESTONE, LIMEY DOLOMITE, FINELY TO COARSELY CRYSTALLINE, MASSIVELY BEDDED, AND THIN BEDDED SHALE.	
		WARSAW FORMATION (3)	60 - 90		SHALE AND THIN TO MEDIUM BEDDED FINELY CRYSTALLINE LIMESTONE WITH INTERBEDDED CHERT.	
	OSAGEAN	BURLINGTON AND KEOKUK LIMESTONES	100 - 200		CHERTY LIMESTONE, VERY FINE TO VERY COARSELY CRYSTALLINE, FOSSILIFEROUS, THICKLY BEDDED TO MASSIVE.	SHALLOW AQUIFER SYSTEM
		FERN GLEN LIMESTONE	45 - 70		CHERTY LIMESTONE, DOLOMITIC IN PART, VERY FINE TO VERY COARSELY CRYSTALLINE, MEDIUM TO THICKLY BEDDED.	
	KINDERHOOKIAN	CHOUTEAU LIMESTONE	20 - 50		DOLOMITIC, ARGILLACEOUS LIMESTONE, FINELY CRYSTALLINE; THIN TO MEDIUM BEDDED.	UPPER LEAKY CONFINING UNIT
DEVONIAN	UPPER	SULPHUR SPRINGS GROUP (4) BUSHBERG SANDSTONE	40 - 55		QUARTZ ARENITE, FINE TO MEDIUM GRAINED, FRIABLE.	
		LOWER PART OF SULPHUR SPRINGS GROUP (UNDIFFERENTIATED)			CALCAREOUS SILTSTONE, SANDSTONE, OOLITIC LIMESTONE, AND HARD CARBONACEOUS SHALE.	
ORDOVICIAN	CINCINNATIAN	MAQUOKETA SHALE (5)	10 - 30		CALCAREOUS TO DOLOMITIC SILTY SHALE AND MUDSTONE, THINLY LAMINATED TO MASSIVE.	
	CHAMPLAINIAN	KIMMSWICK LIMESTONE	70 - 100		LIMESTONE, COARSELY CRYSTALLINE, MEDIUM TO THICKLY BEDDED, FOSSILIFEROUS AND CHERTY NEAR BASE.	MIDDLE AQUIFER SYSTEM
		DECORAH GROUP	30 - 60		SHALE WITH THIN INTERBEDS OF VERY FINELY CRYSTALLINE LIMESTONE.	LOWER CONFINING UNIT
		PLATTIN LIMESTONE	100 - 130		DOLOMITIC LIMESTONE, VERY FINELY CRYSTALLINE, FOSSILIFEROUS, THINLY BEDDED.	
		JOACHIM DOLOMITE	80 - 135		INTERBEDDED VERY FINELY CRYSTALLINE, THINLY BEDDED DOLOMITE, LIMESTONE, AND SHALE. SANDY AT BASE.	
		ST. PETER SANDSTONE	120 - 150		QUARTZ ARENITE, FINE TO MEDIUM GRAINED, MASSIVE.	DEEP AQUIFER SYSTEM
	CANADIAN	POWELL DOLOMITE	50 - 60		SANDY DOLOMITE, MEDIUM TO FINELY CRYSTALLINE, MINOR CHERT AND SHALE.	
		COTTER DOLOMITE	200 - 250		ARGILLACEOUS, CHERTY DOLOMITE, FINE TO MEDIUM CRYSTALLINE, INTERBEDDED WITH SHALE.	
		JEFFERSON CITY DOLOMITE	160 - 180		DOLOMITE, FINE TO MEDIUM CRYSTALLINE.	
		ROUBIDOUX FORMATION	150 - 170		DOLOMITIC SANDSTONE.	
		GASCONADE DOLOMITE	250		CHERTY DOLOMITE AND ARENACEOUS DOLOMITE (GUNTER MEMBER).	
CAMBRIAN	UPPER	EMINENCE DOLOMITE	200		DOLOMITE, MEDIUM TO COARSELY CRYSTALLINE, MEDIUM BEDDED TO MASSIVE.	
		POTOSI DOLOMITE	100		DOLOMITE, FINE TO MEDIUM CRYSTALLINE, THICKLY BEDDED TO MASSIVE. DRUSY QUARTZ COMMON.	

(1) THICKNESS DATA SOURCES VARY. QUATERNARY UNIT THICKNESS BASED ON ON-SITE DRILLING AND TRENCHING. BURLINGTON AND KEOKUK THROUGH JOACHIM DOLOMITE BASED ON USGS WELLS MW-GS02 AND GS05. ST. PETER SANDSTONE AND BELOW FROM KLEESCHULTE AND EMMETT (REF 54). WARSAW AND SALEM FORMATIONS FROM MISSOURI DNR GEOLOGIC MAP OFM-89-252-GI (REF 53).

(2) GLACIAL DRIFT UNIT IS SATURATED IN NORTHERN PORTION OF ORDNANCE WORKS AND BEHAVES LOCALLY AS A LEAKY CONFINING UNIT. (GEOLOGIC LOG)

(3) THE WARSAW AND SALEM FORMATIONS ARE CONSIDERED TO BE ABSENT FROM THE WELDON SPRING AREA DUE TO EROSION.

(4) THE SULPHUR SPRINGS GROUP ALSO INCLUDES THE BACHELOR SANDSTONE AND THE GLEN PARK LIMESTONE. MISSOURI DIVISION OF GEOLOGY AND LAND SURVEY. (REF 53)

(5) THE MAQUOKETA SHALE IS NOT PRESENT IN THE WELDON SPRING AREA BASED ON GEOLOGIC LOGS.

FIGURE 8-1 Regional Stratigraphy and Hydrostratigraphy of the Weldon Spring Area

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The Kimmswick Limestone is medium to coarsely crystalline, highly fossiliferous, medium to thickly-bedded, and cherty near the base (Ref. 50). Solution-enlarged vertical to near-vertical joints and joint intersections are characteristic of this formation. Several thin shale zones are present at the base of the Kimmswick Limestone. The upper portion of this unit has been eroded in the quarry area. The Kimmswick Limestone, where present, ranges from 8 ft to 70 ft thick in the study area.

Underlying the Kimmswick Limestone is the Decorah Group which is a thin to medium-bedded finely crystalline to lithographic limestone containing interbedded clayey, fossiliferous shales (Ref. 50). This formation ranges from 15 ft to 36 ft thick as indicated by coring. A thin metabentonite layer is present near the base of this formation.

The Plattin Limestone conformably underlies the Decorah Group and is a thin to medium bedded, finely crystalline to lithographic limestone with some chert. The lower 5 ft to 10 ft of this formation is a dolomitic, oolitic, argillaceous limestone with thin pebble conglomerate beds. The formation ranges from 82 ft to 121 ft thick, as indicated by rock cores. Solution-enlarged joints have been documented in the Plattin Limestone (Ref. 50), although none were identified in rock cores from the quarry area.

The Joachim Dolomite is predominantly a thinly bedded, yellowish-brown, argillaceous dolomite containing interbedded limestone and shale. Only the upper 15 ft of the Joachim Dolomite was investigated. Literature indicates the typical thickness of the formation ranges from 90 ft to 110 ft (Ref. 1).

Cross sections of the quarry area (Figures 8-2 and 8-3) illustrate the current geologic model. Of particular interest is the sloping surface along the alluvium-bedrock contact. The lower portion of the Kimmswick Limestone and the Decorah Group is present beneath the alluvium north of the slough. The Plattin Limestone, which was eroded by the Missouri River, forms the base of the alluvium south of the slough.

The bedrock topography map (Figure 8-4) shows the effects of natural erosional processes in the quarry area independent of the formation. In addition, man-made depressions (including the quarry) are evident. Zones where intense weathering and erosion have occurred are represented by rapid changes in bedrock surface elevations. The most obvious of these is along the edge of the floodplain where the limestone bedrock has been eroded by the Missouri River to form the bluffs north of the Katy Trail. South of the bluffs, the bedrock surface slopes gradually beneath the alluvium until just south of the Femme Osage Slough where it flattens even further to the southeast.

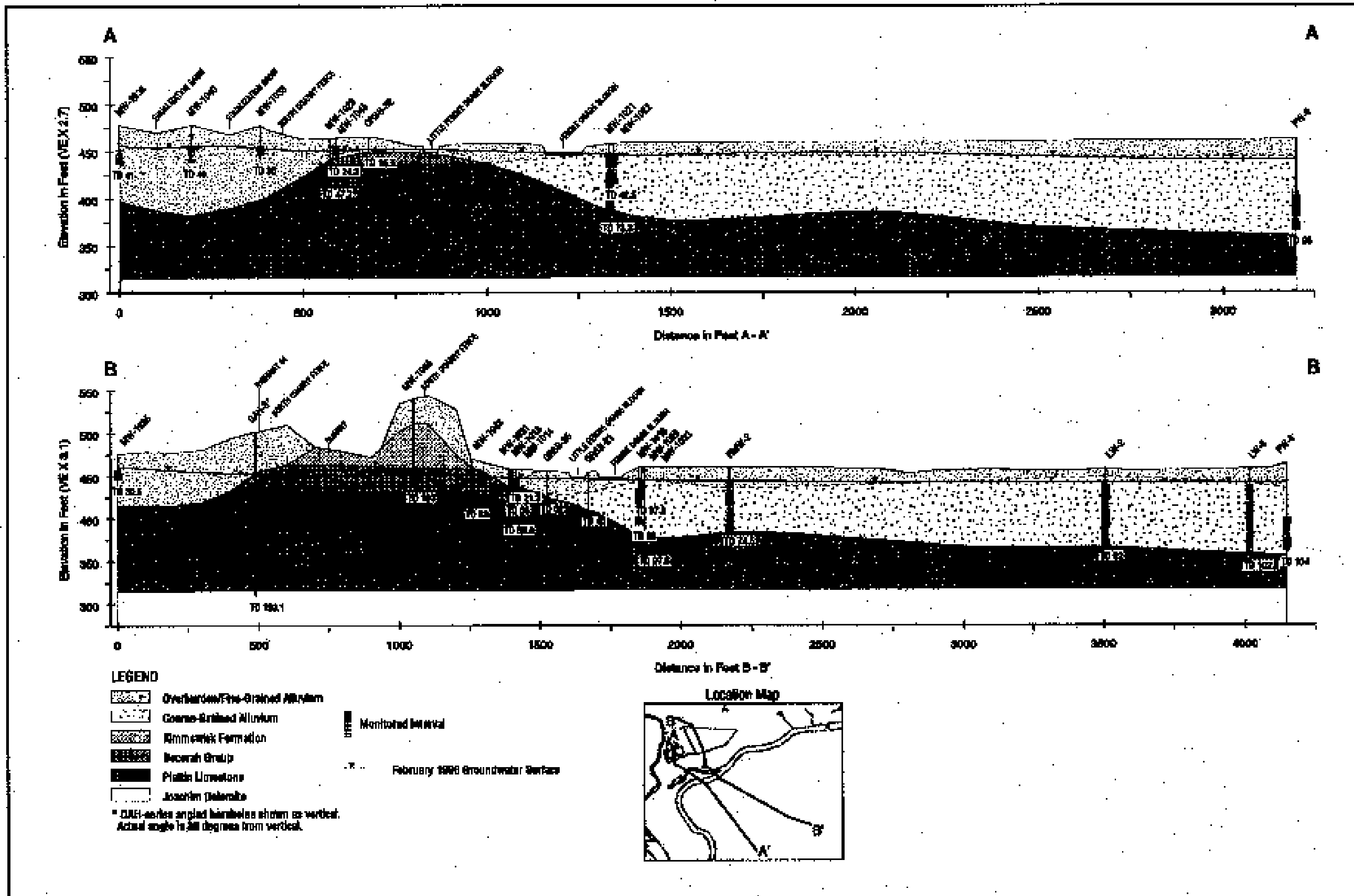

FIGURE 8-2 Hydrogeologic Cross-Sections A and B Through the Quarry

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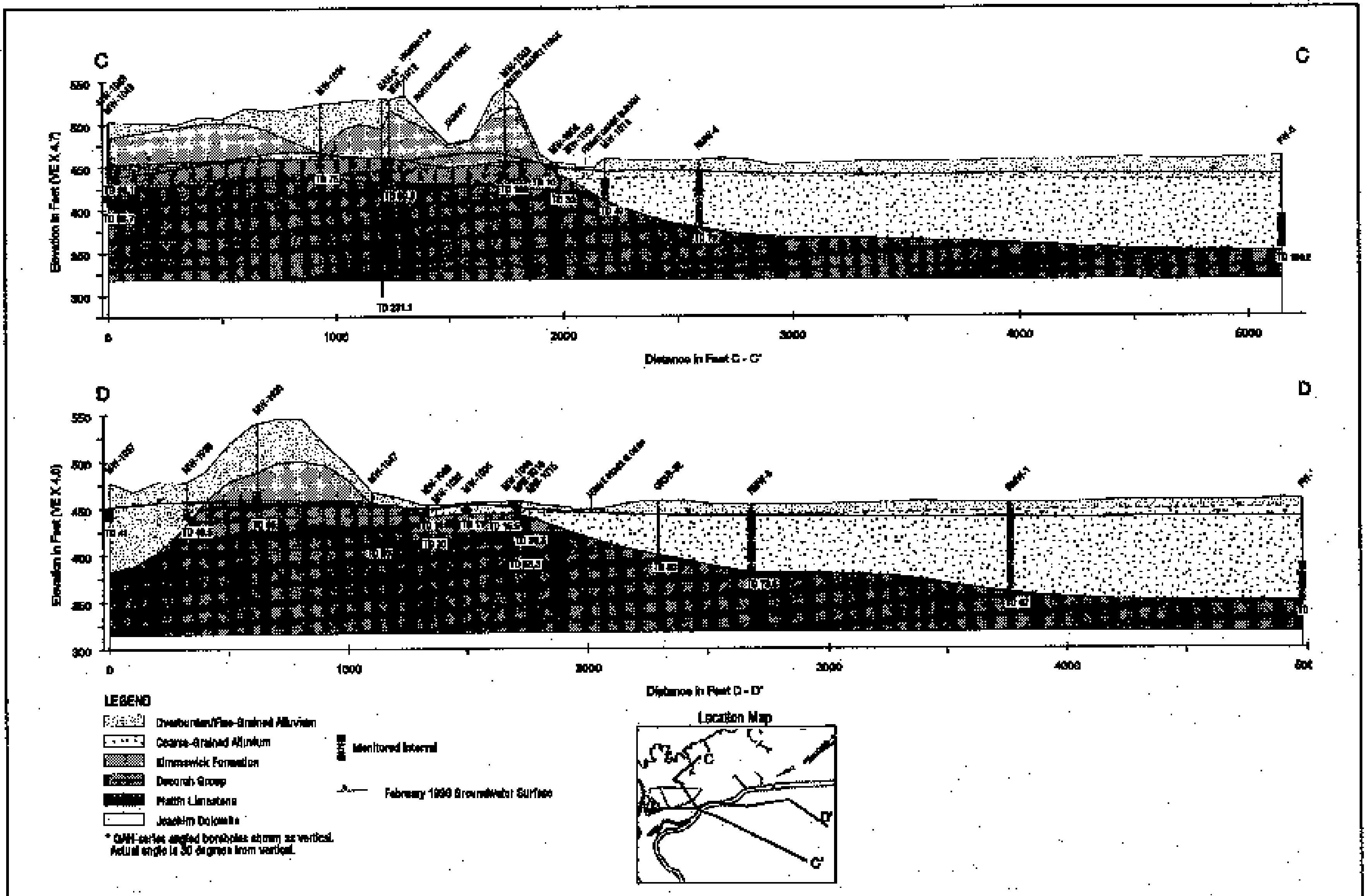

FIGURE 8-3 Hydrogeologic Cross-Sections C and D Through the Quarry Area

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Smaller depressions represent more localized weathering, which is often linearly oriented and represents intense weathering along near-vertical fractures. An example can be seen immediately west of the quarry near the Little Femme Osage Creek (Figure 8-4). In this area, a tributary creek has likely eroded the bedrock in a northeast to southwest direction and deposited alluvium in the erosional valley. This valley forms the northwest side of a bedrock ridge that parallels the valley and extends out into the floodplain. Where saturated, these linear bedrock lows control the direction and velocity of groundwater flow.

A geophysical survey was performed on the Missouri River floodplain south of the quarry to determine the topography of the underlying bedrock surface (Ref. 52). The results of this survey indicate that the bedrock has an undulating surface with occasional ridges and troughs that are likely the result of channel-controlled erosion along the ancient meanders of the Missouri River. On average, bedrock depths determined from the geophysical survey are within 5 ft of depths obtained from field borings.

8.1.2 Hydrostratigraphy

8.1.2.1 Regional. The hydrostratigraphy in the Weldon Spring area is presented in Figure 8-1. The Kimmswick Limestone is the middle aquifer, and the Decorah Group, Plattin Limestone, and Joachim Dolomite comprise the lower confining unit that overlies the deep aquifer system (Figure 8-1). Confining conditions result, in part, from low permeability shale layers in the Decorah Group (Ref. 49). Although saturated, the Decorah Group, Plattin Limestone, and Joachim Dolomite are not utilized as a source of potable water due to extremely low yields (Ref. 49). The Kimmswick Limestone yields small to moderate quantities of water to wells in the surrounding region (Ref. 49).

The deep aquifer system (Figure 8-1) includes units from the St. Peter Sandstone down to the Potosi Dolomite and is one of the most productive aquifers in Missouri (Ref. 49). The deep aquifer is used by many municipalities and public water supply companies, primarily in western and northern St. Charles County (Ref. 49).

The alluvial aquifer underlies the floodplain of the Missouri River and is capable of supplying large quantities of water (600 to 2,600 gpm per well) for municipal, industrial, or domestic use (Ref. 49).

8.1.2.2 Local. Water bearing units in the vicinity of the quarry include limestone bedrock (Decorah Group and Plattin Limestone) and Missouri River alluvium, which are in contact with each other along an erosional surface (Figures 8-2 and 8-3). In the vicinity of the quarry, the Kimmswick Limestone is typically unsaturated, or the water table is near the base of the formation. Although saturated, the Decorah Group, Plattin Limestone, and Joachim Dolomite are not utilized locally as a water source because their yields are extremely low (Ref. 49).

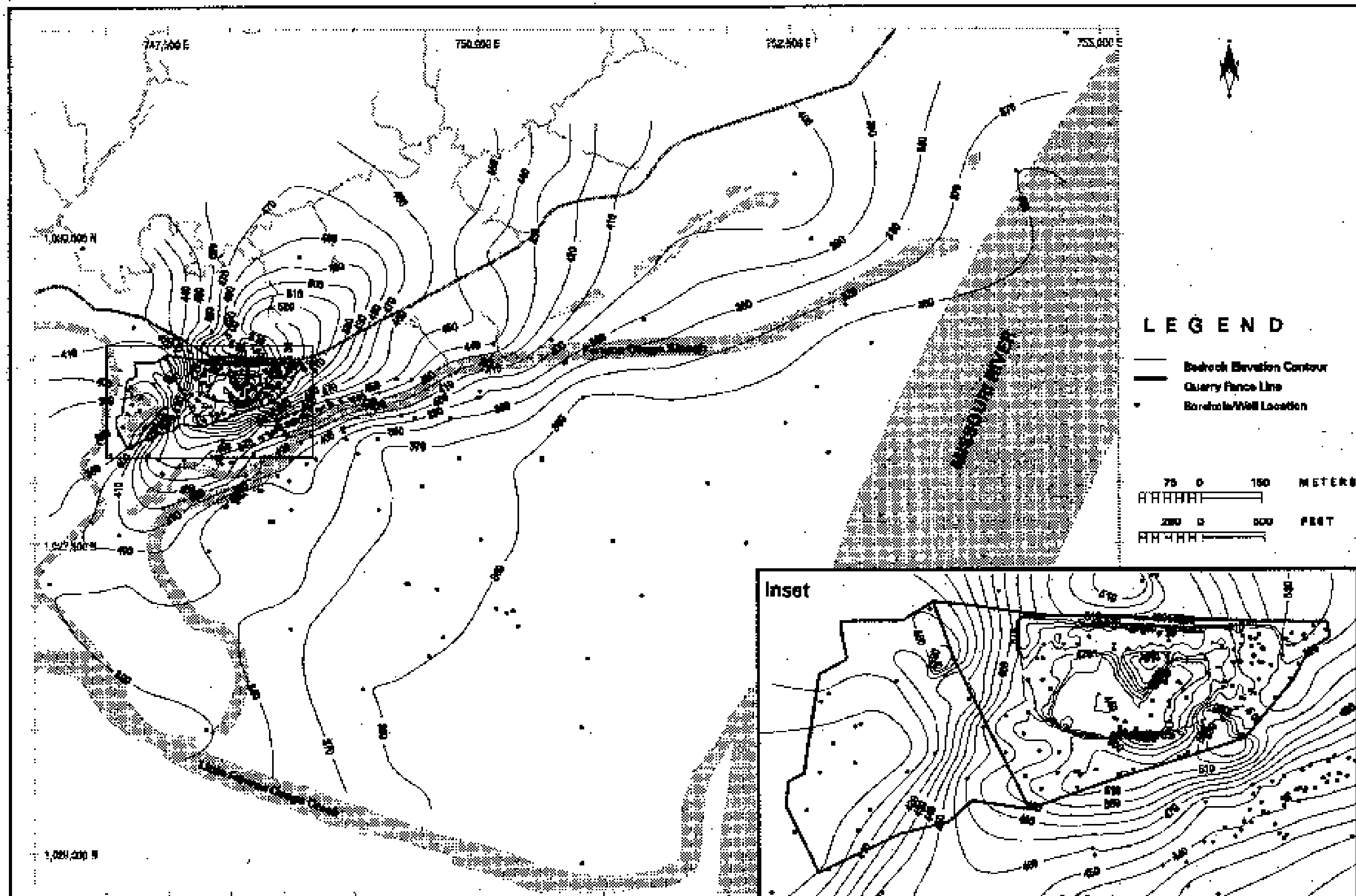

FIGURE 8-4 Bedrock Topography in the Quarry Area

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The alluvial aquifer of the Missouri River valley is a major source of drinking water for St. Charles County. The county currently operates eight production wells capable of producing 22 million gallons per day (MGD) at peak demand. The capacity of the associated water treatment plant, which is north of the well field, is 22 MGD. Typically, only four or five of the wells are used on a rotating basis, producing 10.5 MGD (Ref. 53).

8.1.3 Aquifer Recharge and Discharge

The limestone bedrock units (Kimmswick Limestone, Decorah Group, and Plattin Limestone) are recharged by the following mechanisms:

- Downward flow from the overlying shallow aquifer system (Burlington-Keokuk Limestone and Fern Glen Formation) through the upper leaky confining unit in upland areas to the north.
- Infiltration of both precipitation and runoff through the overburden in the vicinity of the quarry.
- Infiltration of precipitation directly into the bedrock fractures in and near the quarry.
- Infiltration of quarry pond water.

The alluvial aquifer is recharged by the following mechanisms:

- Infiltration of surface water (e.g., the Femme Osage Slough and the Missouri River).
- Infiltration of precipitation.
- Discharge from the limestone bedrock.

Measurements from piezometers installed between the St. Charles County well field and the Missouri River show infiltration from the river into the alluvium (Ref. 54). An electrical analog model of the St. Charles County well field showed that under normal operation 66% of the water pumped is induced infiltration from the Missouri River (Ref. 54). The model also indicates that the percentage of water derived from the river increases as the rate of production increases (Ref. 54).

8.2 Previous Investigations

Numerous hydrogeologic investigations have been performed in the vicinity of the quarry to characterize the uppermost groundwater and refine the understanding of groundwater flow and contaminant migration. An extensive monitoring well network (Figure 8-5), primarily utilized to

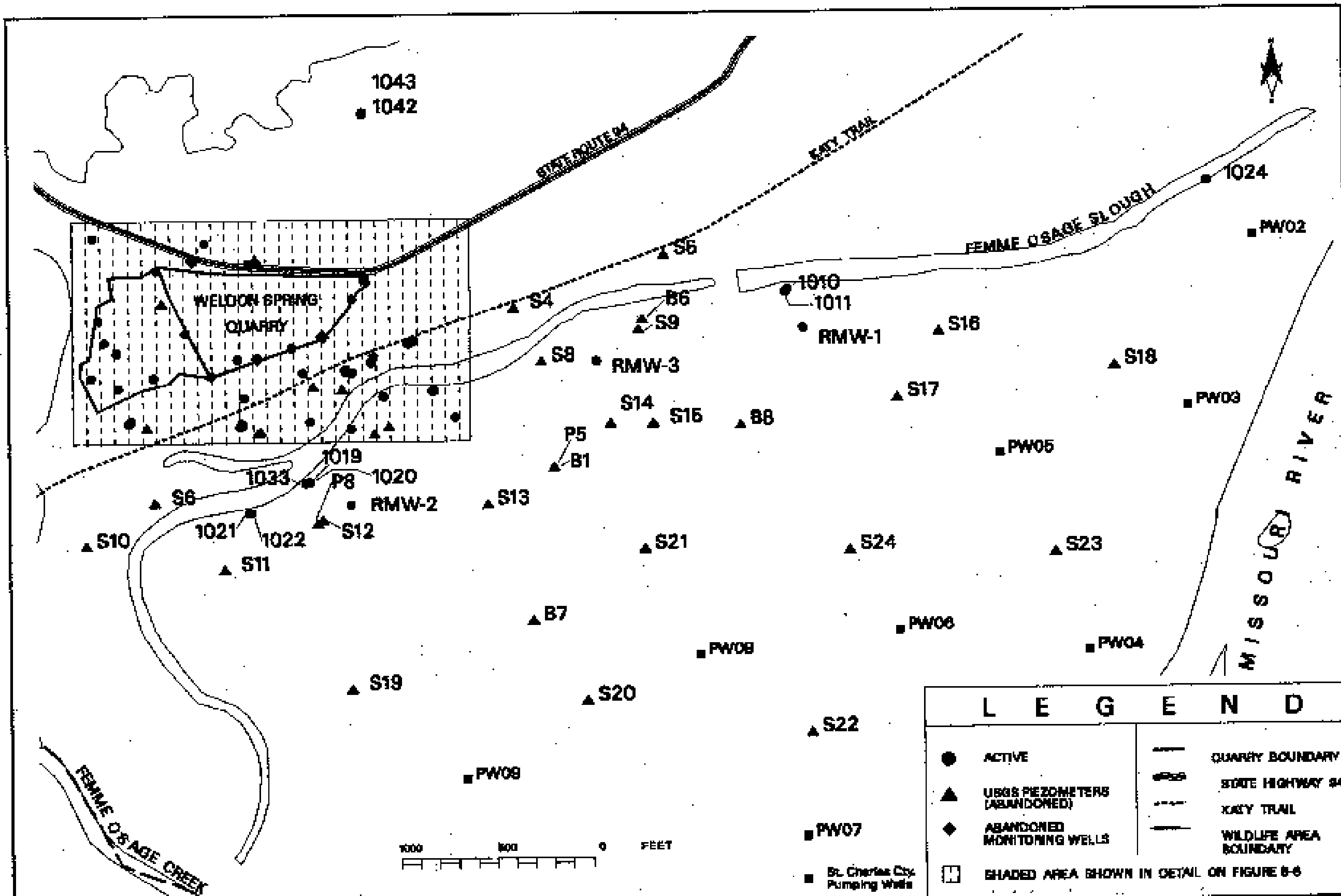

FIGURE 8-5 Monitoring Well and Piezometer Locations in the Quarry Area

DOE/OR/21548-587

monitor groundwater quality, is present at the quarry. A detailed discussion of the monitoring network is presented in Appendix G and a list of monitoring wells is provided in Table G-1 of Appendix G. Additional piezometers were installed and later abandoned by the U.S. Geological Survey (USGS) in an investigation of the groundwater system in the quarry and well field areas. A summary of previous investigations is provided in Table G-2 of Appendix G.

8.3 Remedial Investigations

Hydrogeologic investigations were performed to characterize the physical factors affecting the distribution, fate, and transport of contaminants in the vicinity of the quarry. The testing locations and monitoring wells in the area immediately around the quarry are shown in Figure 8-6. A summary of the hydrogeologic characterization tasks is presented in Table G-3 of Appendix G.

8.3.1 Potentiometric Surfaces and Direction of Groundwater Flow

During this remedial investigation, water levels were measured in a total of 87 alluvial and bedrock monitoring wells and piezometers to determine the distribution of hydraulic head in the underlying aquifer. The typical depth to water ranges from 10 ft to 15 ft in the well field and 75 ft to 100 ft along the quarry rim. The large difference in depth to water is in part a reflection of the land surface elevation which is approximately 100 feet higher along the quarry rim.

Several general observations can be made about groundwater levels which are independent of the temporal conditions:

- Groundwater levels measured in the bedrock along the southern rim of the quarry are consistently higher than levels measured in the alluvium.

- Groundwater levels in the alluvium north of the Femme Osage Slough are higher than those measured in the alluvium south of the slough.

- Groundwater levels in the bedrock of the quarry rim are consistently higher in the eastern portion compared to those in the western portion.

The potentiometric surface maps reflect three hydrologic conditions (Figures 8-7 through 8-9): (1) normal or typical water levels, (2) low water (drought), and (3) high water (flood). The maps illustrate the fact that the most significant response of the system to each condition is fluctuation in groundwater levels; however, flow direction generally is not influenced by seasonal variations. Groundwater flow direction is consistently south to southeast from the bedrock into the alluvium. Groundwater flow is to the west and south from the northeast corner of the quarry. South of the slough, the direction of groundwater flow has an increasing eastward component, likely due to the influence of the Missouri River and/or pumping in the St. Charles County well field.

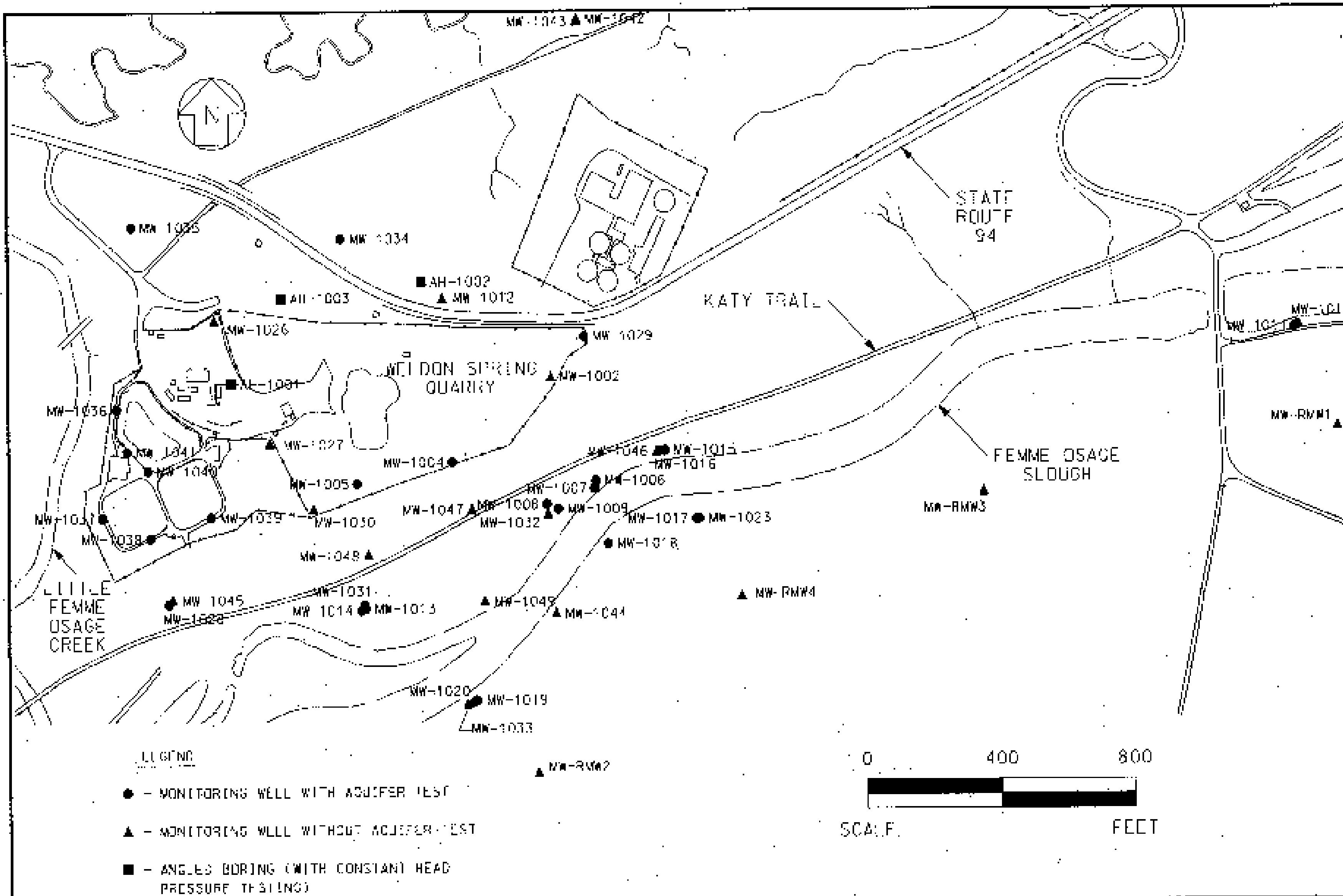

FIGURE 8-6 Hydrogeologic Investigation Testing Locations

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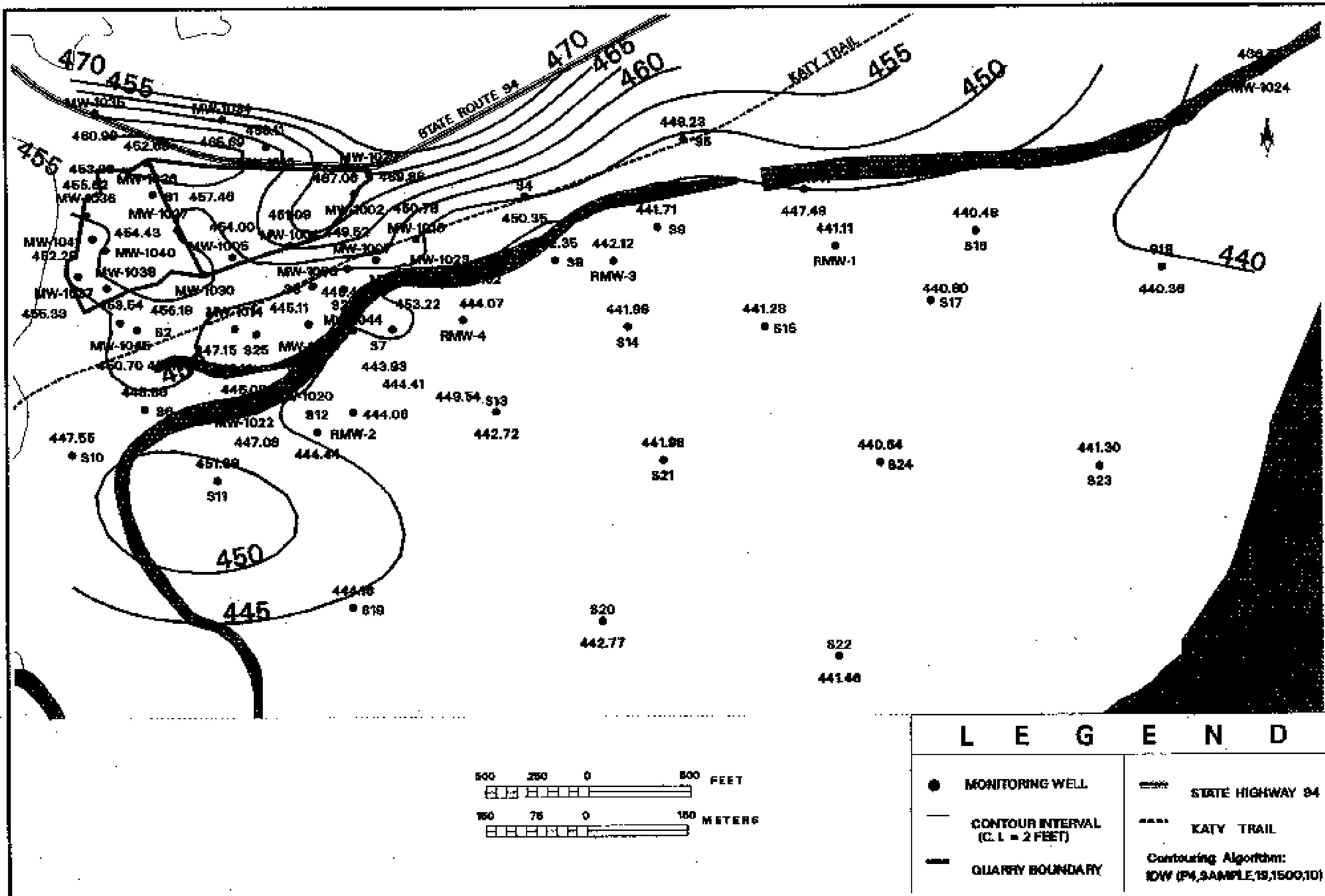

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FIGURE 8-7 POTENTIOMETRIC SURFACE OF THE SHALLOW AQUIFER: FEBRUARY 1996 (TYPICAL)

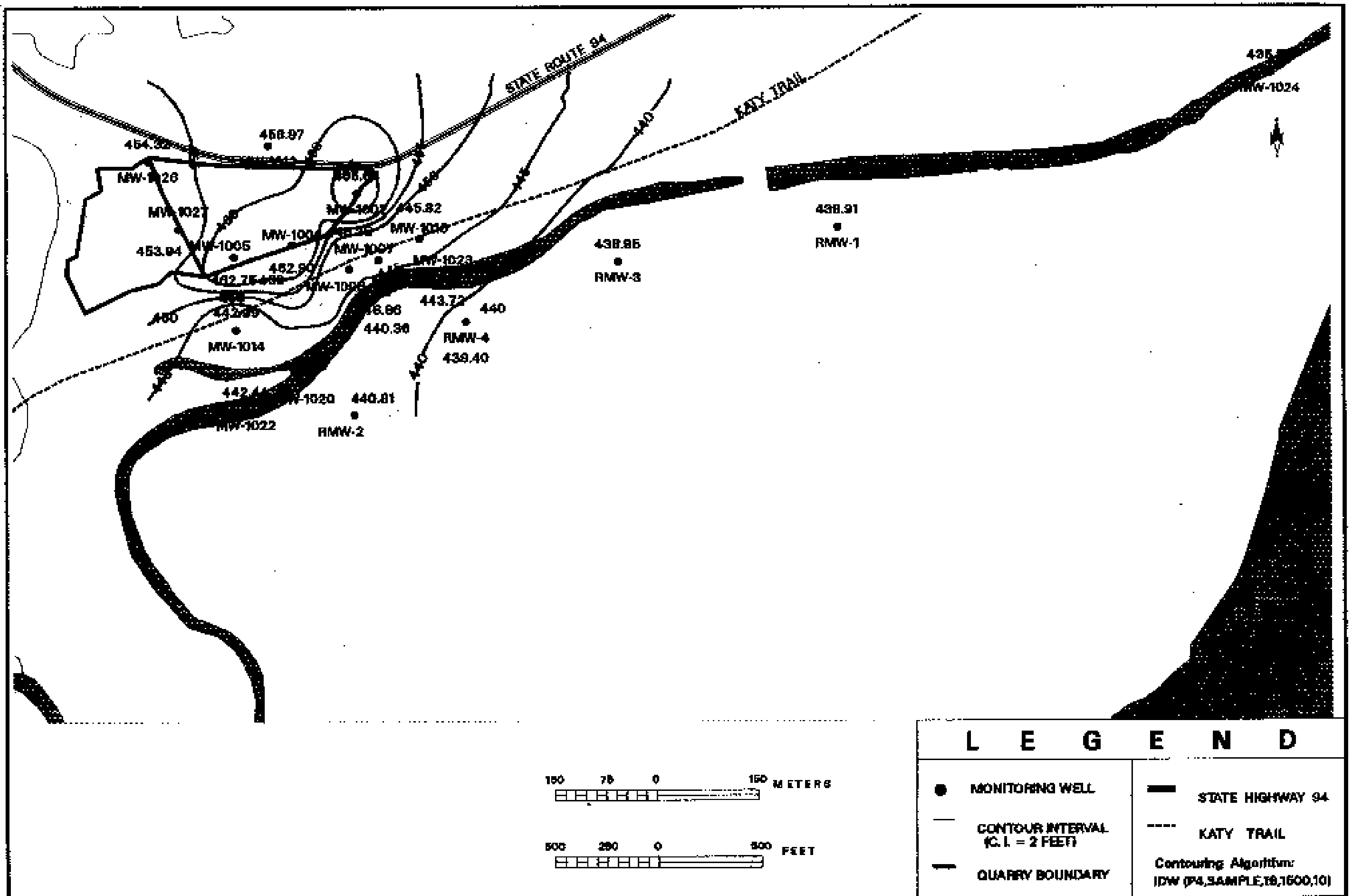

FIGURE 8-8 POTENTIOMETRIC SURFACE OF THE SHALLOW AQUIFER: OCTOBER 1988 (LOW WATER)

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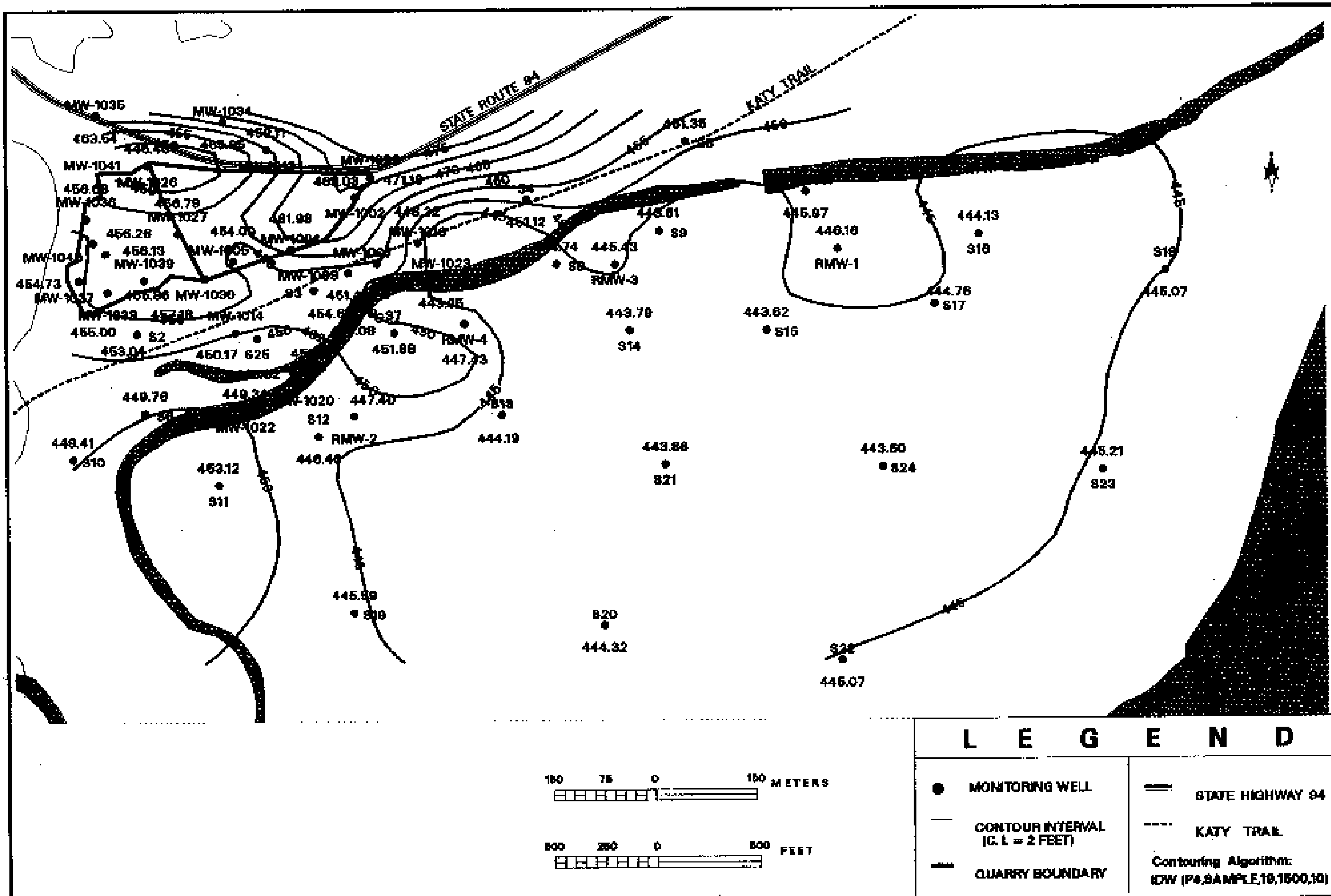

FIGURE 8-9 **POTENTIOMETRIC SURFACE OF THE SHALLOW AQUIFER: APRIL 1995 (HIGH WATER)**

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The map for February 1996 illustrates the typical potentiometric surface for the shallow aquifer in the vicinity of the quarry (Figure 8-7). Data from this month were selected because groundwater levels are within typical ranges for the area, and additional static water level data are available from a USGS study (Ref. 46). Dewatering during bulk waste removal has depressed the groundwater surface around the quarry pond. A steep hydraulic gradient occurs in the bedrock while the gradient in the alluvium is gradual. Groundwater mounds are evident around two piezometers (S-7 and S-11) south of the slough and coincide with a thick sequence of blue clay observed during installation of these piezometers (Ref. 46). The clay is similar to materials observed near the Little Femme Osage Creek and may be a relic of a former tributary creek in the floodplain. These clays may allow for localized perched or confining conditions in this area (Ref. 46).

Data from October 1988 have been used to illustrate the potentiometric surface in the shallow aquifer during low water level conditions (Figure 8-8). The configuration of the potentiometric surface during this period is similar to that of typical conditions, even with significantly lower water levels, indicating the groundwater flow direction is unchanged.

Data from April 1995 were used to represent high water level conditions (Figure 8-9). These measurements were obtained one month before the Missouri River flooded the area. The potentiometric surface is similar to typical groundwater conditions; however, the gradient within the bedrock is steeper in the eastern part of the quarry. Effects of dewatering are also evident as shown by the depression in the groundwater surface. The influence of high stage of the Missouri River and pumping in the well field can be seen in the water levels of piezometers adjacent to the river (S-16, S-22, and S-23). These conditions result in a reversal of the gradient. The reversal is also present, but to a lesser degree, during typical conditions. The gradient in the alluvium is relatively flat, and groundwater mounding is evident around piezometers S-7 and S-11, as discussed above.

Hydrographs of well clusters in the vicinity of the quarry were used to determine the vertical head distribution between and within the bedrock and alluvium and were constructed from data obtained from 1987 through 1996 (Figures 8-10 through 8-14). North of the slough, the hydraulic head within the alluvium generally decreases with depth, indicating downward movement of groundwater. Within the alluvium south of the slough, the hydraulic head also decreases with depth. Closer to the river, the hydraulic head within the alluvium is uniform or increases with depth, indicating the vertical component of movement is negligible, and the horizontal flow component is predominant.

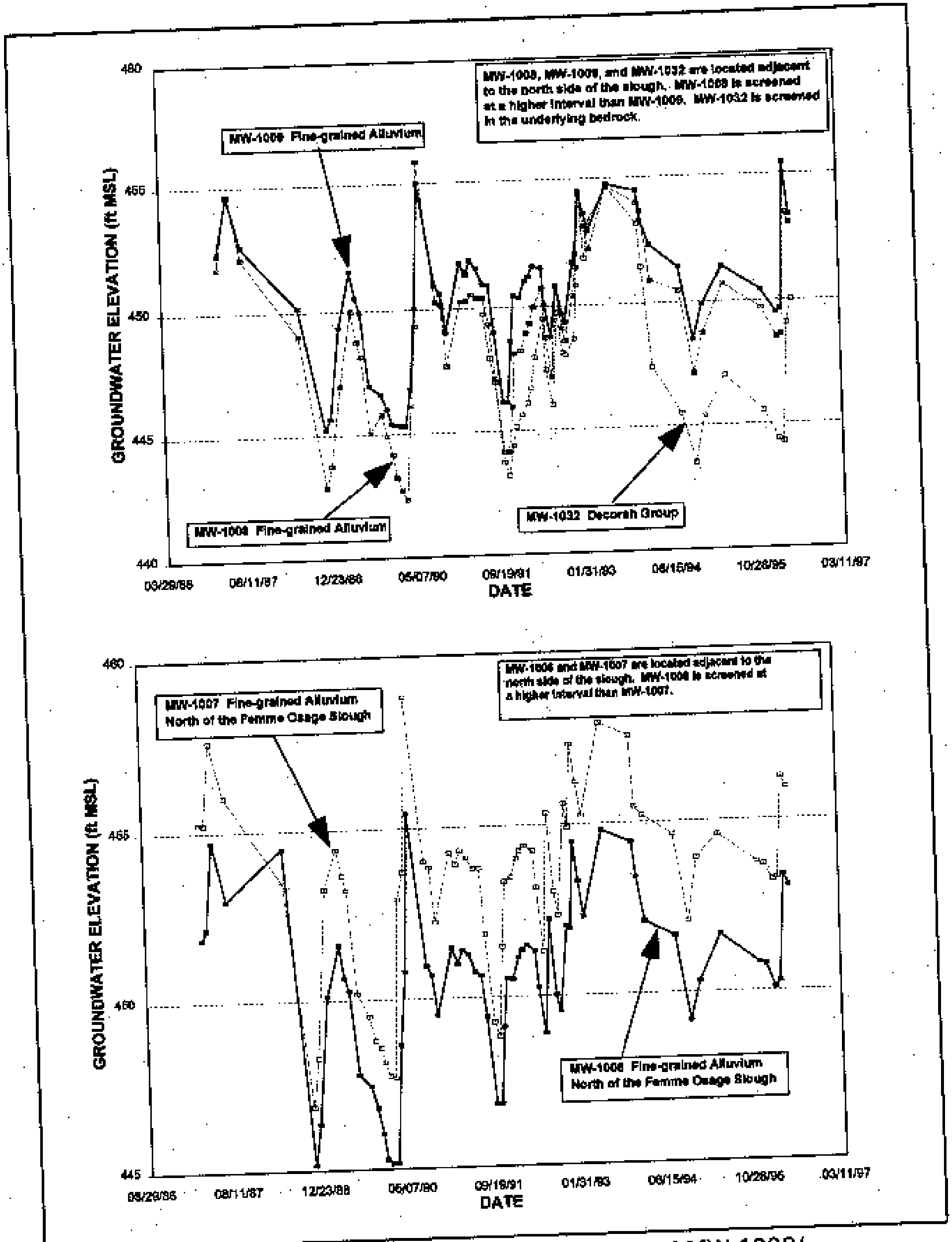

FIGURE 8-10 Hydrographs: MW-1006/MW-1007 and MW-1008/MW-1009/MW-1032

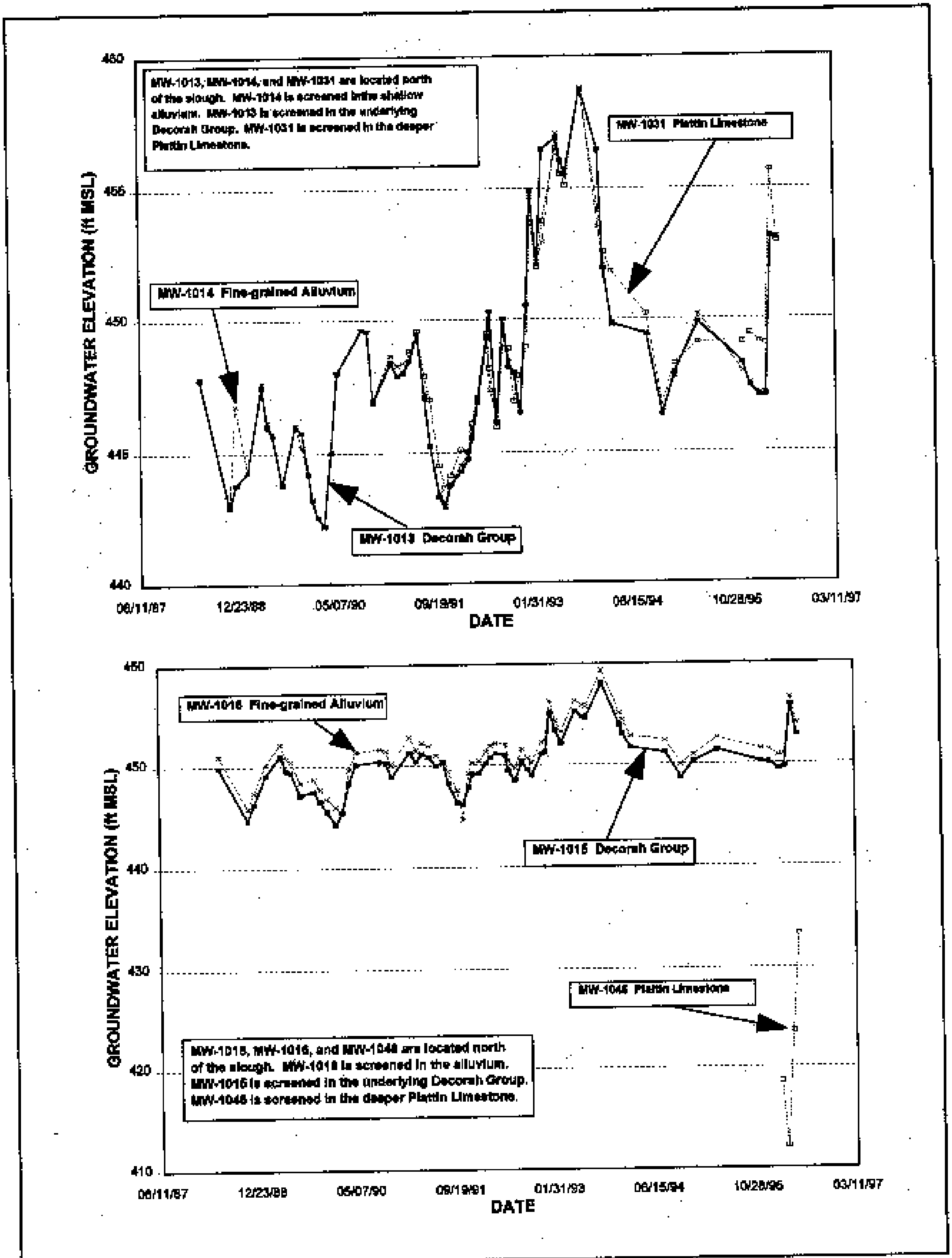

FIGURE 8-11 Hydrographs: MW-1013/MW-1014/MW-1031 and MW-1015/MW-1016/MW-1046

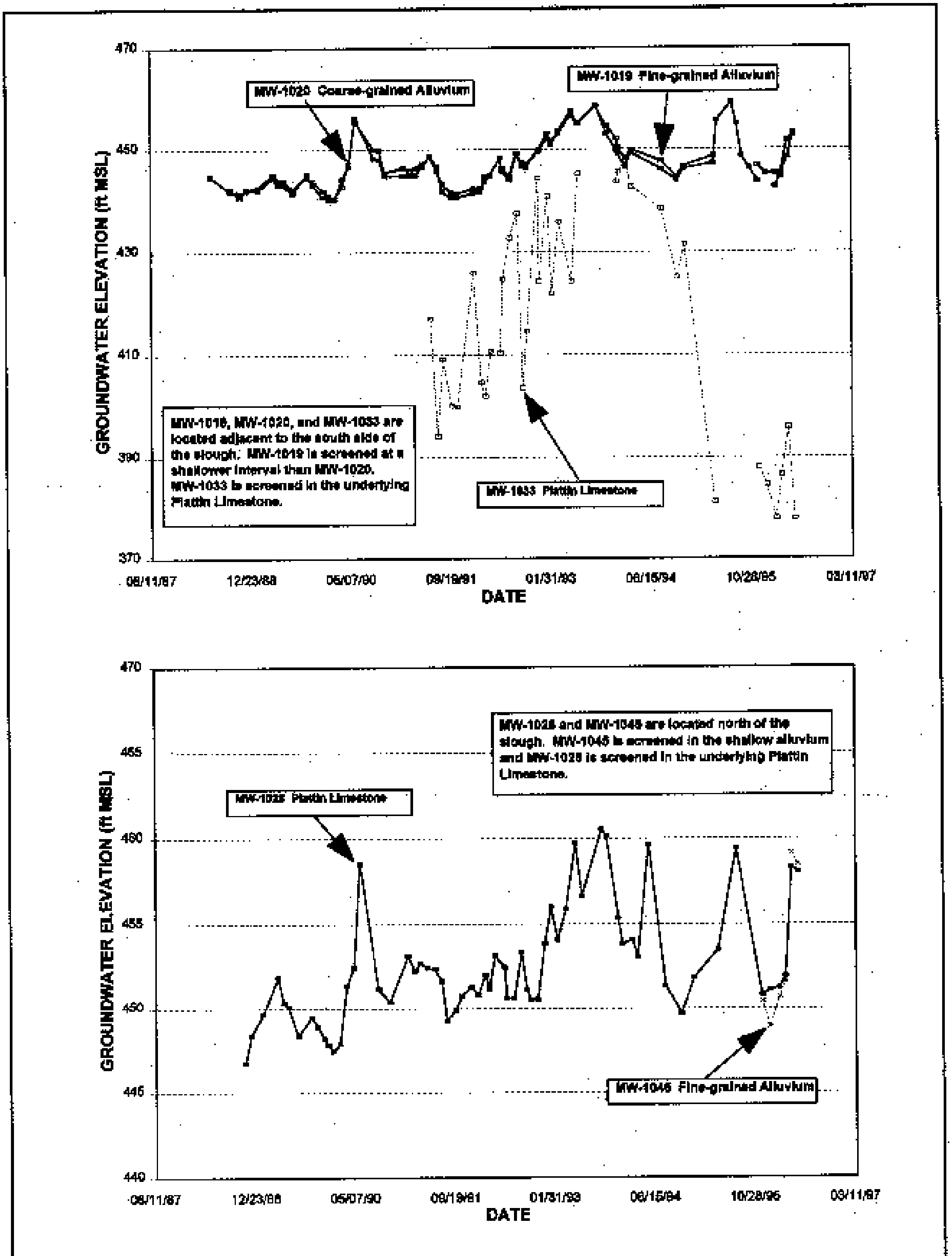

FIGURE 8-12 Hydrographs: MW-1019/MW-1020/MW-1033 and MW-1028/MW-1045

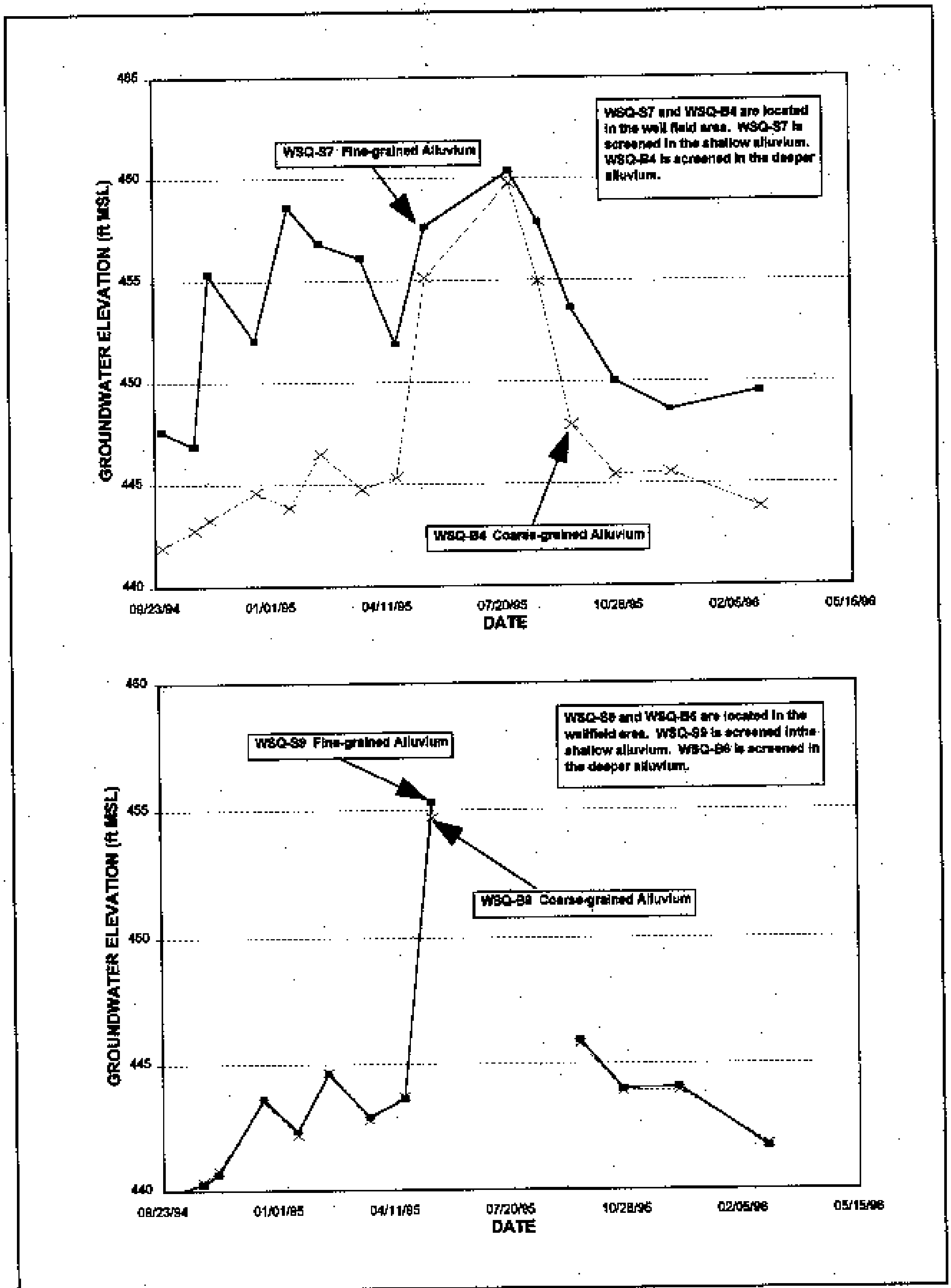

FIGURE 8-13 Hydrographs: WSQ-S9/WSQ-B6 and WSQ-S7/WSQ-B4

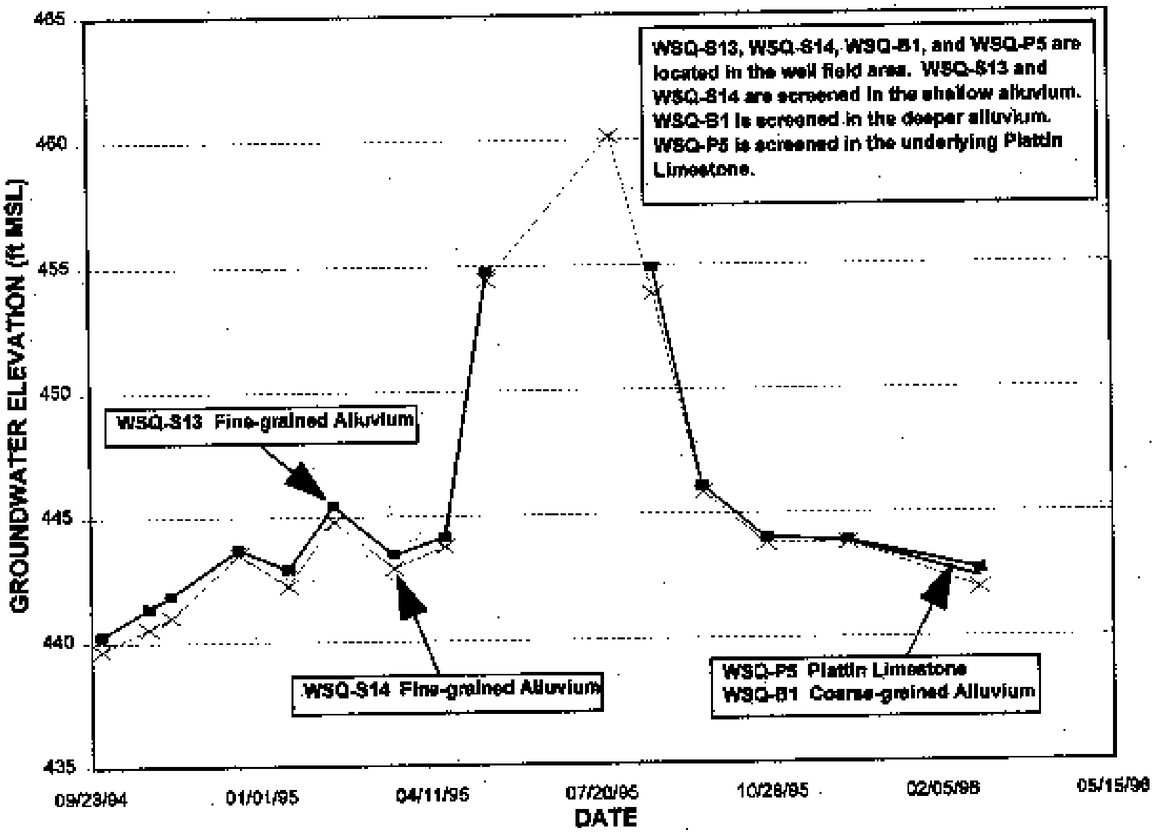

FIGURE 8-14 Hydrograph: WSQ-S13/WSQ-S14/WSQ-B1/WSQ-P5

In the bedrock north of the slough, the hydraulic head in the Decorah Group is less than, or equal to, that in the overlying alluvium. This indicates that these units likely act as one hydrologic unit due to weathering and fracturing of the bedrock, and that downward movement occurs in this localized area. The hydraulic head in the Plattin Limestone is higher than in the overlying alluvium indicating discharge from the bedrock into the alluvium. South of the slough, the head distribution is difficult to assess due to the slow stabilization of water levels in bedrock piezometers, although it is believed that the Plattin Limestone discharges groundwater upward to the alluvium.

8.3.2 Interaction of Groundwater and Surface Water at the Femme Osage Slough

A comparison of typical static water levels in wells adjacent to the slough and the surface water elevation of the slough indicates that at most locations, the slough is a source of recharge to the alluvial aquifer (Figure 8-15) (i.e., slough levels are higher than groundwater levels).

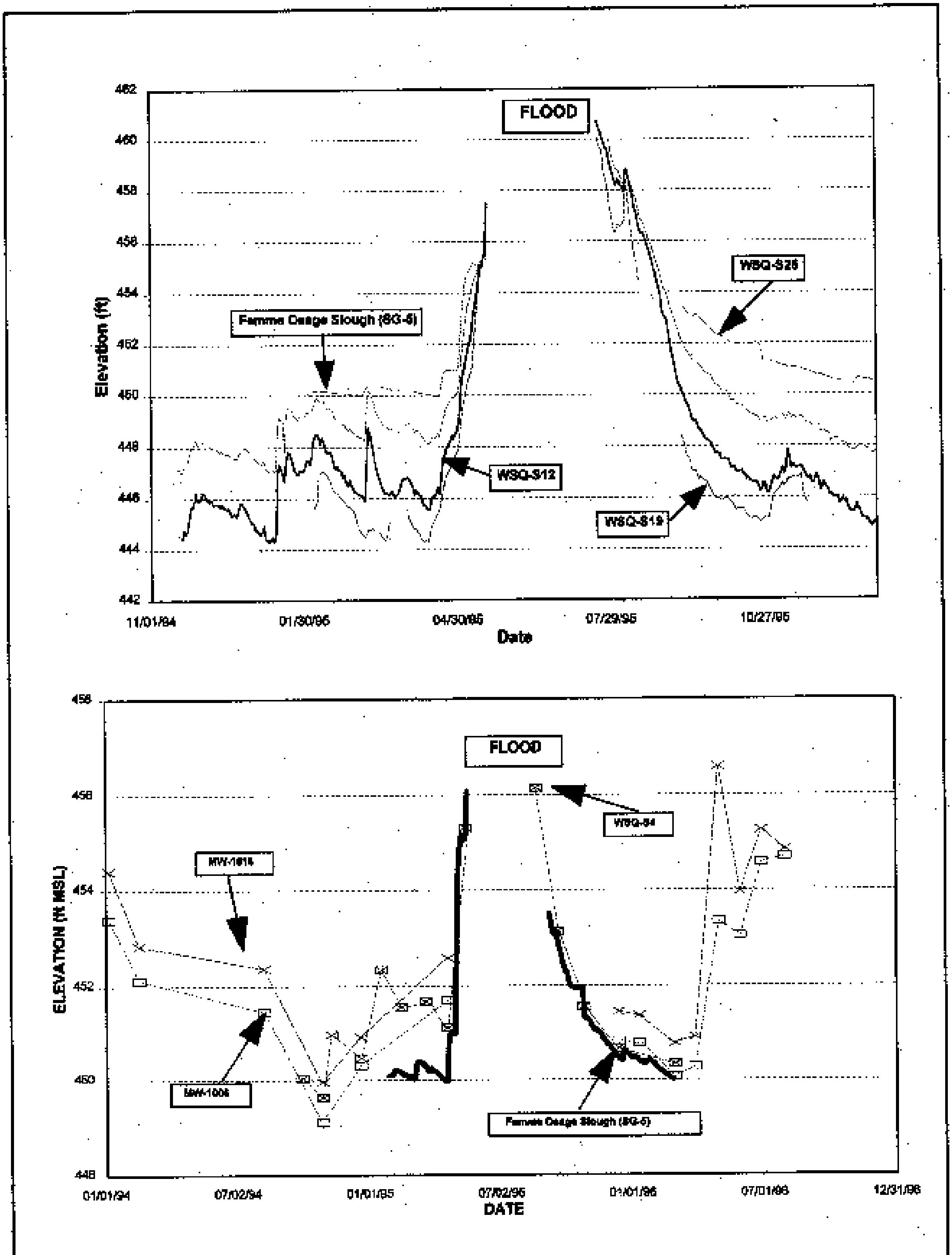

FIGURE 8-15 Hydrographs: MW-1006/MW-1016/WSQ-S4/SG-5 and WSQ-S25/WSQ-S12/WSQ-S19/SG-5

However, groundwater discharge to the slough occurs in some locations as shown by the hydrograph of wells MW-1006 and MW-1016, piezometer WSQ-S4, and staff gage SG-5. Hydrographs for these wells and the slough indicate that the groundwater levels are higher than the surface water levels in this area during normal conditions.

8.3.3 Hydraulic Properties

The hydraulic conductivity, transmissivity, and specific yield of the alluvium and bedrock units have been measured by constant-head packer tests, slug tests, and constant rate discharge and recovery tests. The procedures for determining these aquifer properties are described in Appendix G.

8.3.3.1 Bedrock. Packer tests were performed during the drilling of angled borings and recently installed monitoring wells to determine the range of hydraulic conductivity for the bedrock units. The range of values and median hydraulic conductivity for each bedrock unit are summarized in Table 8-1. Hydraulic conductivity values are summarized for each tested interval in Appendix G (Table G-4). Test results are also presented in Appendix G.

TABLE 8-1 Hydraulic Conductivity Ranges from Packer Tests in the Bedrock Units at the Quarry

UNIT	HYDRAULIC CONDUCTIVITY (cm/s)		
	MAXIMUM	MINIMUM	MEDIAN
Kimmswick Limestone	2.1×10^{-3}	2.0×10^{-4}	1.2×10^{-3}
Decorah Group	5.1×10^{-4}	6.5×10^{-7}	3.6×10^{-5}
Plattin Limestone	4.0×10^{-4}	5.5×10^{-8}	1.5×10^{-5}
Joachim Dolomite	6.7×10^{-5}	1.4×10^{-5}	2.9×10^{-5}

The test results indicate that hydraulic conductivity is consistently higher in the Kimmswick Limestone than the other units and is associated with open fractures. Many of the fractures exhibit evidence of groundwater movement. Hydraulic conductivity in the Decorah Group, Plattin Limestone, and Joachim Dolomite is variable within each unit and is a function of fracture density and aperture. Numerous tight fractures, which had little water intake, were observed during coring and testing of the Decorah Group, Plattin Limestone, and Joachim Formation.

Slug tests were also performed on bedrock wells, and the results, which are presented in Tables G-5 and G-6 of Appendix G, are generally within the ranges obtained from the packer tests. However, hydraulic conductivity values obtained from slug tests at monitoring wells MW-1013 (Decorah Group) and MW-1031 (Plattin Limestone) were higher than the ranges for those strata established from the packer tests. At these locations, the Decorah Group and Plattin Limestone are the uppermost bedrock units, and weathering has most likely increased the hydraulic conductivity.

8.3.3.2 **Alluvium.** Slug tests were performed in the alluvial wells to determine the areal and vertical distribution of hydraulic conductivity. Results presented on Figure 8-16, show:

- Hydraulic conductivity ranges from 10^{-4} cm/s to 10^{-3} cm/s in the alluvium south of the slough.
- Hydraulic conductivity is more variable north of the slough, ranging from 10^{-5} cm/s to 10^{-3} cm/s.
- Hydraulic conductivity generally increases with depth (up to one order of magnitude).
- The hydraulic conductivity of the shallow alluvium along the Little Femme Osage Creek ranges from 10^{-5} cm/s to 10^{-3} cm/s and generally increases with distance from the quarry.

Hydraulic conductivity in the alluvium is variable and shows a direct correlation to grain size. Variability in hydraulic conductivity is related to complex depositional patterns resulting from streams and rivers that have meandered across the floodplain. Areas of fine-grained material, such as overbank or flood deposits, generally exhibit lower hydraulic conductivities than coarse-grained point bar or channel deposits. Typically, grain size and hydraulic conductivity increase with depth in the alluvium.

Aquifer testing in the alluvium north of the slough was performed to further define aquifer properties. Step drawdown/recovery tests were performed on six wells (MW-1006 through MW-1009, MW-1014, and MW-1016) and a 6-hour constant-rate discharge and recovery test was performed on MW-1016. Yields greater than 0.5 gallons per minute (gpm) could not be maintained in monitoring wells MW-1006 through MW-1009; therefore, aquifer properties were not determined at these locations.

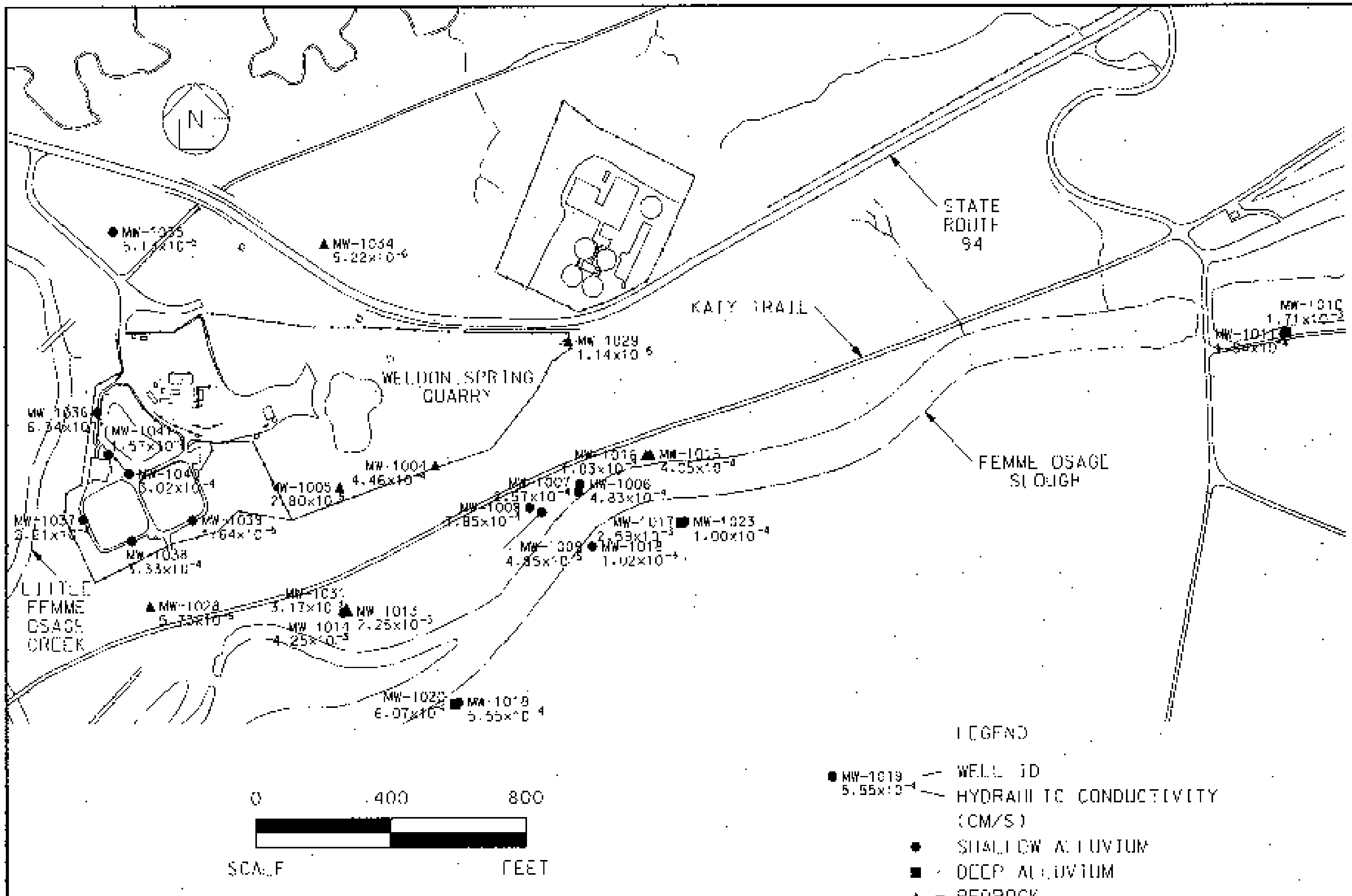

FIGURE 8-16 Distribution of Hydraulic Conductivity from Slug Testing in the Quarry Area

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The results of tests at MW-1014 and MW-1016 are summarized in Table 8-2. While testing the alluvium at MW-1016, a decrease in the static water level was noted in an adjacent well (MW-1015) which is screened in the Decorah Group. This response demonstrates hydraulic connection between the materials at the base of the alluvium and the underlying bedrock system.

Constant rate discharge tests were also performed by Layne Western in 1985 (Ref. 54) and Bechtel in 1986 (Ref. 55) in the alluvial aquifer south of the slough (in the well field), and the results are included in Table 8-2. Layne Western performed pumping tests to evaluate the hydraulic properties of the coarse-grained deposits in the lower portion of the alluvial aquifer. The testing by Bechtel was performed to evaluate the hydraulic characteristics of the alluvium directly south of the slough.

TABLE 8-2 Hydraulic Properties of the Alluvium

WELL	HYDRAULIC CONDUCTIVITY (cm/s)		TRANSMISSIVITY (gpd/ft)		SPECIFIC YIELD
	PUMPING	RECOVERY	PUMPING	RECOVERY	
MW-1014	6.4×10^{-3}	7.5×10^{-3}	680	800	— [a]
MW-1016	4.2×10^{-3}	3.2×10^{-3}	440	340	— [a]
Well Field[b]	2.0×10^{-1}		6,000 - 465,000		0.2 - 0.35
Well Field[c]	8.2×10^{-3}		6957		0.005

Note (a) Length of testing was insufficient for determination of specific yield
(b) Source: Ref. 54
(c) Source: Ref. 55

8.3.4 Fracture Flow

Groundwater movement in limestone in the vicinity of the quarry occurs primarily within fractures and along bedding planes. This movement has resulted in solution enlargement of these features in the Kimmswick Limestone.

The orientations of fractures, solution features, and bedding planes provide information on the principal directions of groundwater flow. Fractures observed in the Kimmswick Limestone at the quarry walls are both horizontal (bedding plane) and vertical to near vertical. Vertical fracture apertures become tighter with depth, especially at the contact with the underlying Decorah Group. Intersections of vertical fractures with bedding planes generally show enlargement due to solution activity.

8.3.4.1 Fracture Mapping. Fracture mapping and lineament analysis of aerial photographs were performed on the exposed walls of the quarry and bluffs prior to bulk waste removal. Additional fracture maps of the quarry walls were prepared after the bulk waste was removed to determine vertical fracture trends and potential preferential flow zones in the lower portion of the Kimmswick Limestone and in the Decorah Group.

A total of 85 vertical fractures, fracture zones, and solution features were evaluated during mapping along the inner quarry walls and the bluffs adjacent to the Katy Trail. The locations and directions of fractures mapped in the quarry area are shown on Figure 8-17. A summary of the bearing, aperture, and other pertinent information from this effort is provided in Appendix G, Table G-7. A rose diagram (Figure 8-17) illustrates that the predominant joint set in the quarry area is oriented between N50°W to N60°W. These joints are nearly vertical and have an average spacing of 50 ft. Two secondary vertical joint sets are also present, with orientations ranging from N60°E to N70°E and N60°W to N70°W. Most of these joints were measured in the Kimmswick Limestone, but traces into the Decorah Group could be observed inside the quarry.

Open fractures were observed on the walls and the quarry floor in the Kimmswick Limestone. Fracture apertures, which are dependent on the amount of weathering, range from less than 0.2 ft to 4 ft. Clay and silt filling was observed in many vertical fractures both inside and outside the quarry. Fracture surfaces in the Kimmswick Limestone were typically etched, indicating groundwater movement. Fracture traces observed in the Decorah Group on the quarry floor were tight and showed little evidence of water movement.

Numerous fractures were observed along bedding planes in both the Kimmswick Limestone and the Decorah Group. Enlargement due to solution activity was observed along the base of the upper quarry bench at intersections with vertical fractures. Seepage was observed along the top of a shale bed near the contact between the Kimmswick Limestone and the Decorah Group. This seepage indicates that the horizontal component of flow is greater than the vertical component near the contact of these two bedrock units.

During lineament mapping, fracture zones were found to correspond with drainage patterns in the bluffs. These zones likely represent areas of preferential weathering of the Kimmswick Limestone. Large solution features (caves) were observed in the bluff along the Katy Trail. Large zones of core loss and bit drops, which are typically associated with solution features, were encountered during drilling along the south rim of the quarry.

8.3.4.2 Rock Core Fracture Analysis. Three angled borings were advanced at 30° from vertical to assess fracturing in the Kimmswick Limestone, the Decorah Group, and the Plattin Limestone (Figure 8-6). The Joachim Dolomite is not discussed here because it was only slightly penetrated by the angled borings. Fracture aperture, frequency, and orientation were evaluated to determine possible preferential pathways in the bedrock. Rock cores obtained from the angled borings were used in the assessment to alleviate the difficulty of distinguishing horizontal bedding plane fractures from mechanical breaks caused by vertical drilling. Mechanical breaks usually occur perpendicular to the direction of drilling.

Overall, few vertical or near-vertical fractures were encountered in the angled borings. Most fractures were near horizontal bedding-plane fractures. Fracture data for each angled boring are summarized in Table 8-3.

TABLE 8-3 Angled Boring Fracture Data

FORMATION	CORED LENGTH (ft)[a]	AVERAGE FRACTURES (ft)[b]	NUMBER OF FRACTURES		HORIZONTAL/ VERTICAL RATIO
			VERTICAL	HORIZONTAL	
Angled Boring AH-1001					
Plattin Limestone	120.5	1.7	3	204	68 to 1
Angled Boring AH-1002					
Kimmswick Limestone	31.8	3.0	1	96	96 to 1
Decorah Group	32.2	1.2	1	38	38 to 1
Plattin Limestone	133.0	0.8	1	110	110 to 1
Angled Boring AH-1003					
Decorah Group	17.0	3.7	1	63	63 to 1
Plattin Limestone	138.0	1.1	7	156	22 to 1

(a) Length of bedrock cored at an angle of 30° from vertical. Does not include void space or overburden drilling.
(b) Average fractures per foot of bedrock cored.

Results from angled borings indicate that the greatest number of fractures occur in the Kimmswick Limestone, which had an average frequency of three fractures per ft. The Decorah Group has an average of 2.1 fractures per ft based on the data from angled borings AH-1002 and AH-1003. The average frequency for the Plattin Limestone was 1.2 fractures per ft in the three angled borings.

The horizontal to vertical fracture ratio for a given formation varied significantly between angled borings. Averaged ratios for each formation are as follows:

- Kimmswick Limestone 68 to 1
- Decorah Group 51 to 1
- Plattin Limestone 42 to 1

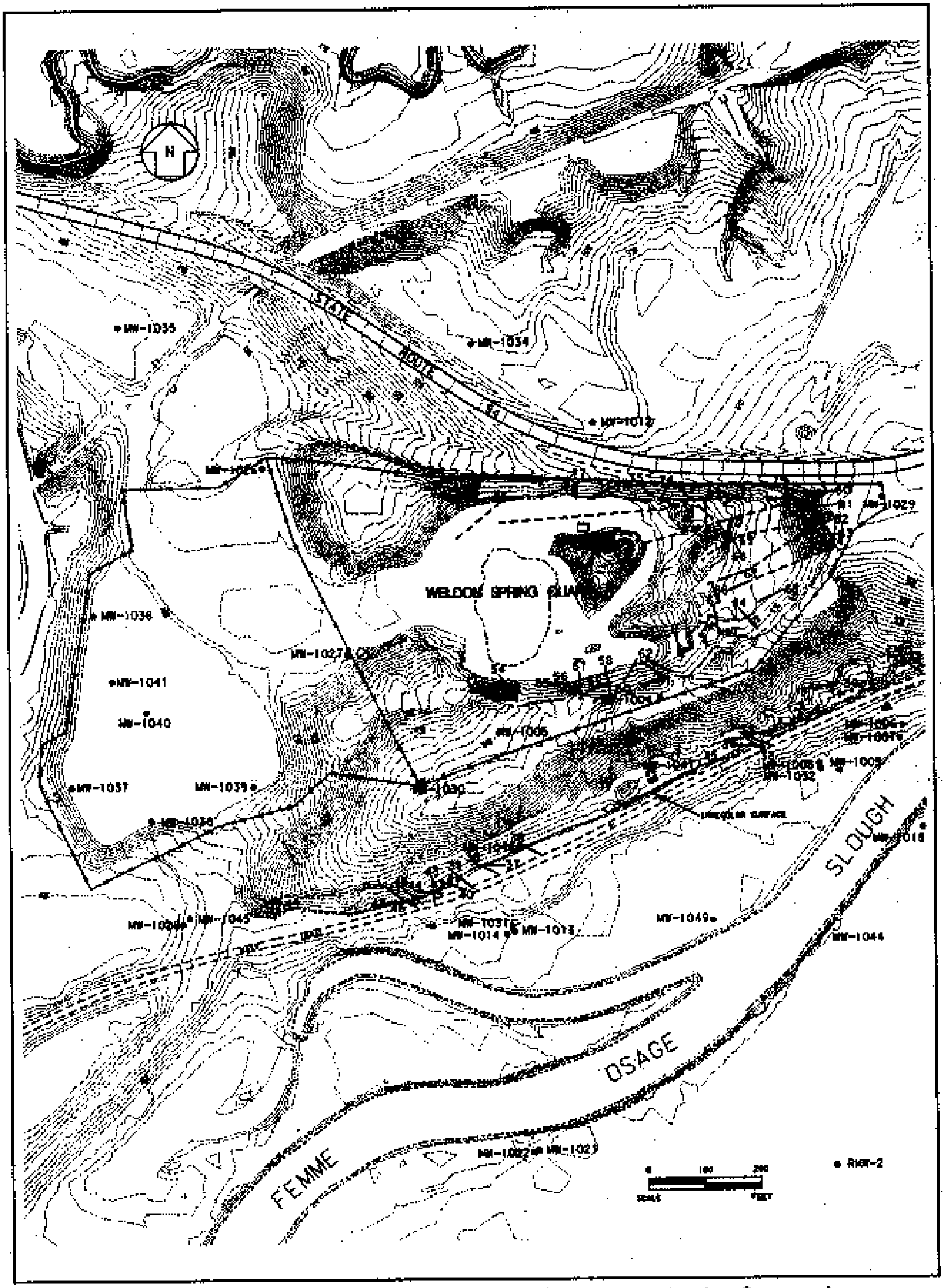

FIGURE 8-17 Locations and Orientations of Fractures in the Quarry Area

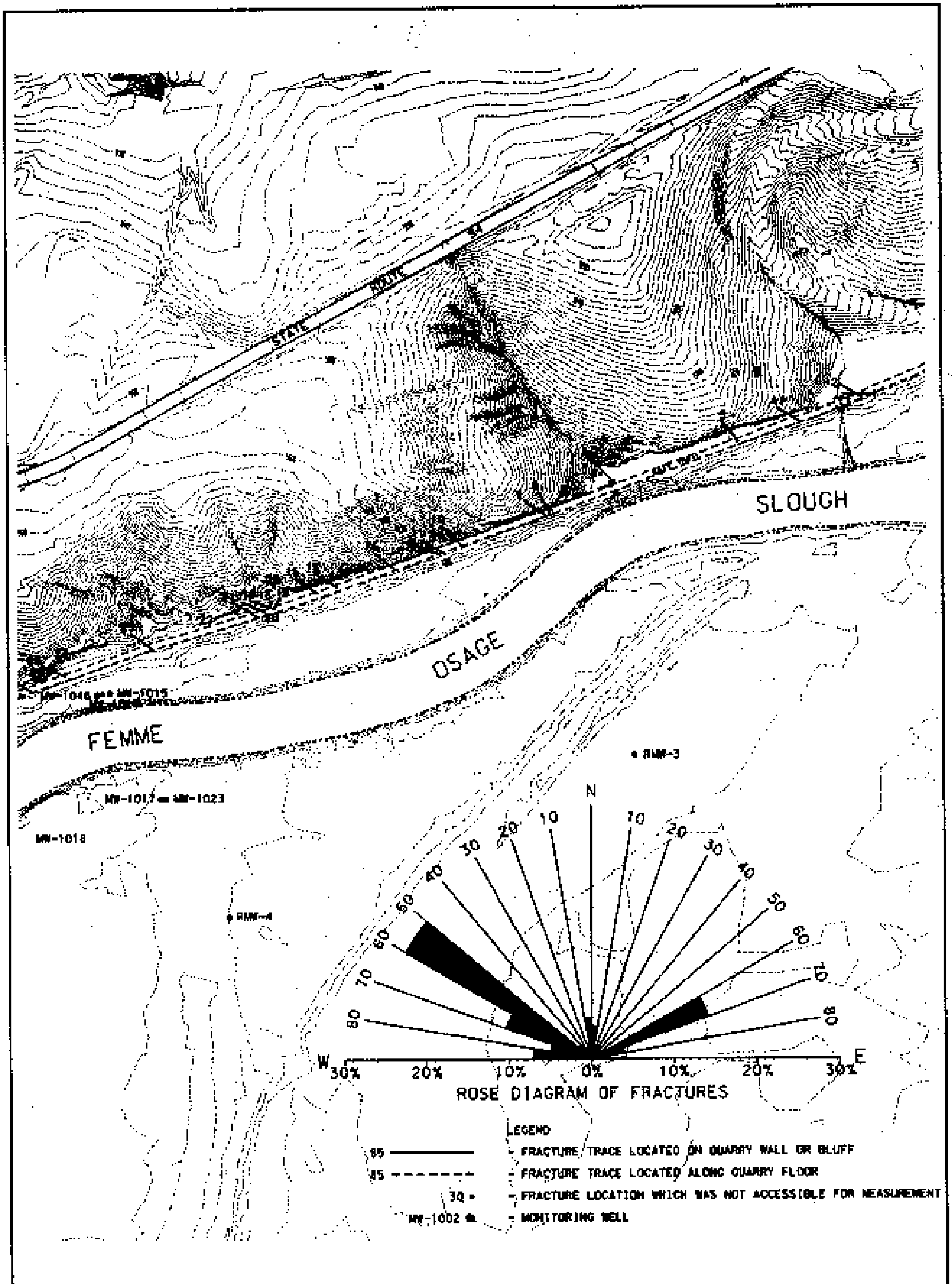

FIGURE 8-17, Continued

The low average horizontal to vertical ratio in the Plattin Limestone is greatly influenced by the number of near-vertical fractures encountered in AH-1003. Most of the fractures were tight or healed with secondary mineralization. Also, the lower frequency of horizontal fractures in the Plattin Limestone tends to reduce the horizontal to vertical fracture ratio.

Analysis of fracture frequencies and horizontal to vertical ratios indicates that the potential for groundwater movement in these units is greater in the horizontal direction. Vertical movement through the Decorah Group and the Plattin Limestone is limited by the low number of near vertical fractures, as observed during coring. Lateral flow is greater in the Kimmswick Limestone and the Decorah Group than in the Plattin Limestone due to the greater frequency of horizontal fractures.

8.3.4.3 **Rock Quality Designation Analysis**. The Rock Quality Designations (RQD) for the bedrock units in the quarry area were evaluated to assess potential groundwater movement. RQD is the cumulative length of solid pieces of rock core 4 in. or longer in a core run, divided by the total length of the core run, and expressed as a percentage. The average RQD values were determined from the three angled borings and seven additional vertical borings throughout the quarry area. The average RQD values for each formation are:

- Kimmswick Limestone 45%
- Decorah Group 79%
- Plattin Limestone 90%

The Kimmswick Limestone exhibited the lowest RQD values, which are associated with the weathered nature of this rock unit. This formation is often the uppermost bedrock encountered in the boring, thus tending to be the most weathered. Advanced dissolution of the medium- to coarsely-crystalline limestone is also a factor contributing to low RQD values. Several boreholes encountered large voids in the Kimmswick Limestone.

In the boreholes analyzed, the RQD values indicate that the rock quality of the Decorah Group is much better than that of the Kimmswick Limestone. This higher RQD is the result of protection from direct weathering by the overlying Kimmswick Limestone. In those borings where the Decorah Group was the first encountered bedrock unit, the RQD values are similar to those measured in the Kimmswick Limestone, indicating that the Decorah Group is highly weathered in these areas (south of the quarry).

The Plattin Limestone exhibits the highest RQD values of the three formations. Even where the Plattin Limestone was the first encountered bedrock unit (south of the slough), the average RQD value was 83% (AH-1001).

Increased fracture frequencies and low RQD values correlate with increased rock weathering and solutioning, particularly in the Kimmswick Limestone. This formation exhibits zones of intense solution activity which likely results in preferential groundwater movement where the formation is saturated. In the Decorah Group, bedding plane fractures dominate and often occur along shaley partings and interbeds which results in more horizontal movement than vertical movement. The Plattin Limestone exhibits the fewest fractures and the highest RQD values. The very fine-grained composition of the Plattin Limestone and its depth below the surface contribute to this characteristic.

8.4 Groundwater Flow Volume

A flow net was constructed from the February 1996 potentiometric surface map and is shown in Figure 8-18. The flow net was used to approximate: (1) the volume of flow that discharges from the bedrock into the alluvial aquifer, and (2) the volume of flow in the alluvial aquifer in the vicinity of the Femme Osage Slough. The volumes were calculated using Darcy's law (Ref. 81):

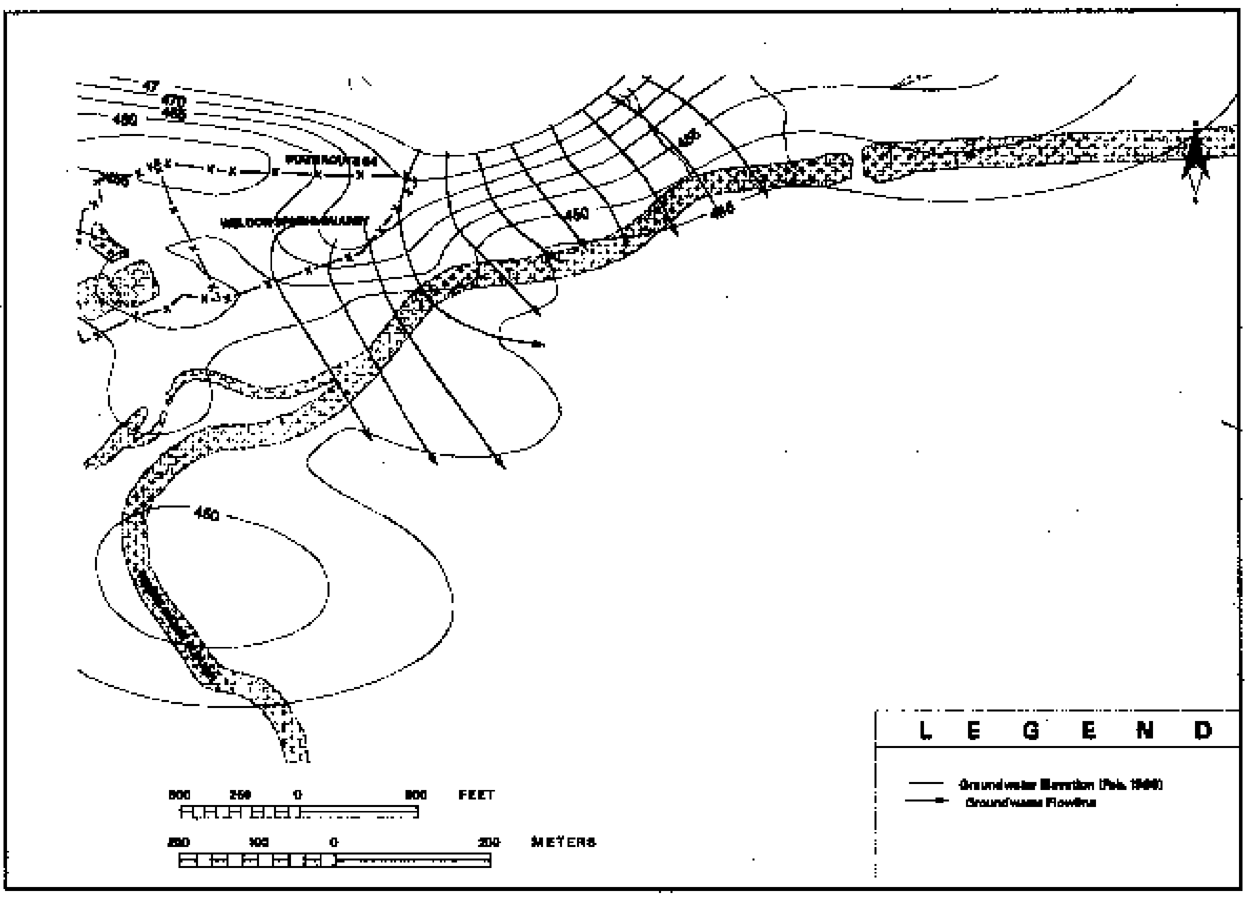

FIGURE 8-18 Flow Net for the Quarry Area - February 1996

$$Q = KAI$$

where:
- Q = flow volume (L^3/T)
- K = hydraulic conductivity (L/T)
- A = cross sectional area (L^2)
- I = hydraulic gradient or change in hydraulic head per length of flow or distance (dimensionless)

Darcy's law can be rewritten as:

$$Q = KbIW$$

where:
- b = aquifer thickness
- W = width of aquifer section

To estimate the volume of flow discharging from the bedrock system to the alluvial aquifer beneath and north of the Femme Osage Slough, it was assumed that the contributing units include the bottom 5 ft of the Kimmswick Limestone, the full thickness of the Decorah Group (34 ft), and the top 20 ft of the Plattin Limestone. This portion of the bedrock system subcrops beneath the alluvium in this area as shown in Figures 8-2 and 8-3 and the conceptual model (Figure 8-19). The hydraulic conductivities used in the calculation were obtained from Table 8-2. An average hydraulic gradient of 15 ft (head loss) per 300 ft (distance) is evident on Figure 8-18 in the area between the 460 ft and 475 ft contour intervals. An 1,860 ft section of the aquifer between the flow lines (Figure 8-18) was also used in the calculation.

To estimate bedrock discharge from the Kimmswick Limestone (K), Decorah Group (D), and Plattin Limestone (P), the equation becomes:

$$Q = [(K_K \times b_K) + (K_D \times b_D) + (K_P \times b_P)] \times I \times W$$

where:
- K_K = 1.15×10^{-3} cm/s or 2.4×10^{3} gal/day/sq ft.
- b_K = 5 ft.
- K_D = 3.64×10^{-5} cm/s or 7.7×10^{1} gal/day/sq ft.
- b_D = 34 ft.
- K_P = 1.45×10^{-5} cm/s or 3.1×10^{-1} gal/day/sq ft.
- b_P = 20 ft.
- I = 15 ft/300 ft.
- W = 1,860 ft.

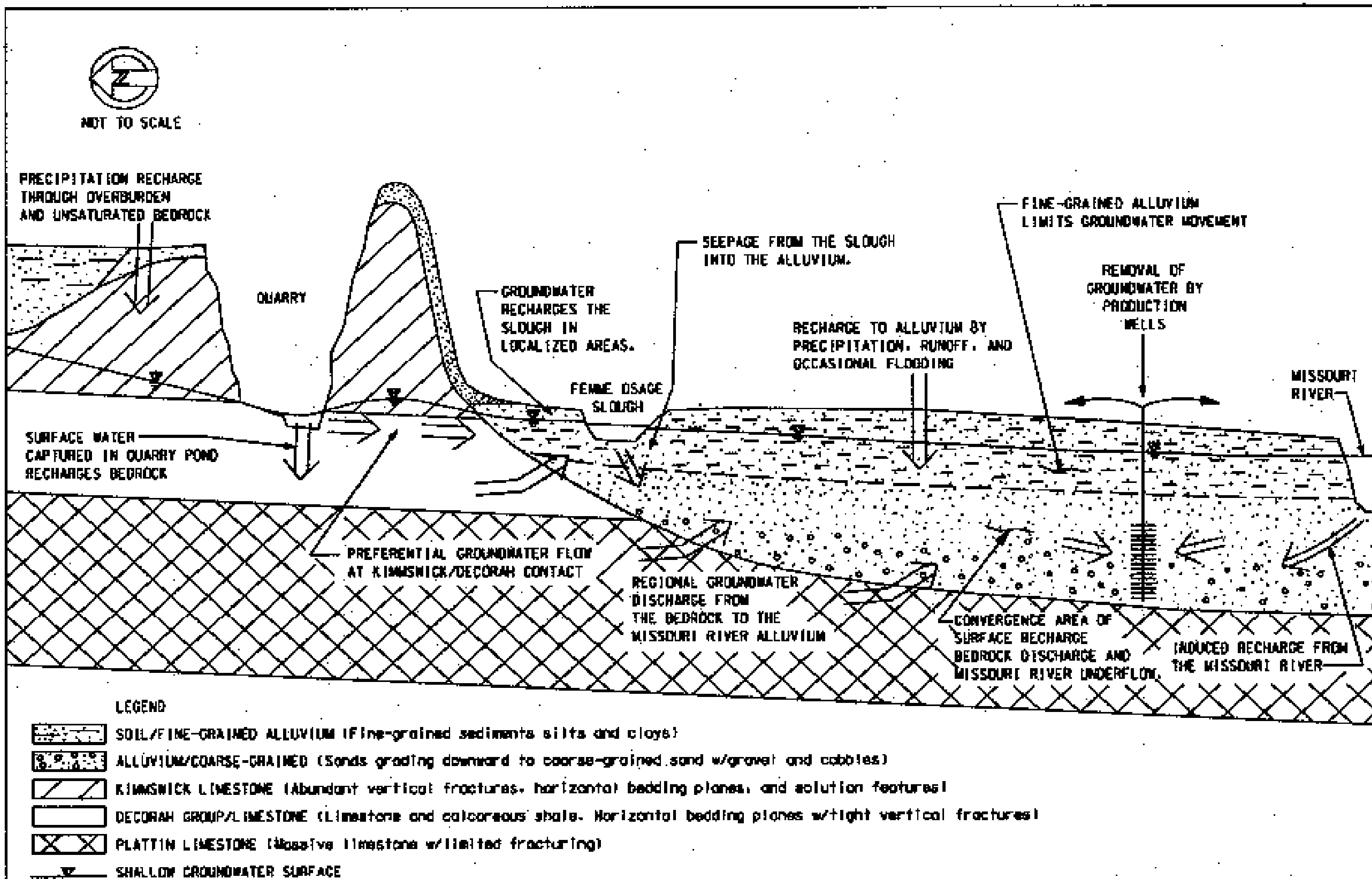

FIGURE 8-19 HYDROGEOLOGIC CONCEPTUAL MODEL FOR THE QUARRY AREA

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The results of the calculation show that the approximate discharge from the upper portion of the bedrock system in the section shown on Figure 8-18 is approximately 14,000 gal/day.

A similar calculation was made to determine the flow volume in the alluvial system near and immediately south of the slough. A median hydraulic conductivity of 6×10^{4} cm/s (1.3×10^{1} gal/day/sq ft) and an average saturated thickness of 35 ft were assumed for the calculation based on data presented in Section 8.3.3.2 and on Figures 8-2, 8-3, and 8-16. An average hydraulic gradient of 5 ft (head loss) per 300 ft (distance) is evident in Figure 8-18 in the area between the 445 ft and 450 ft contour intervals. A 1,860 ft section of the aquifer between the flow lines shown in Figure 8-18 was also used in the calculation.

To estimate the volume of flow in the alluvial system in the vicinity of the Femme Osage Slough, the equation is:

$$Q = KbIW$$

The results of the calculation show that the approximate flow volume in the alluvial aquifer near and immediately south of the slough is 15,000 gal/day, which is slightly higher than the calculated bedrock discharge. The increase in flow in the alluvial aquifer is attributed to leakage from the slough.

Table 8-2 shows that the transmissivity of the alluvial aquifer increases by several orders of magnitude to the south and east of the Femme Osage Slough in the area of the St. Charles County well field and the Missouri River. Correspondingly, the volume of flow in the alluvial aquifer increases in this direction.

8.5 Hydrogeologic Conceptual Model

The conceptual model of the shallow aquifer system incorporates various geologic and hydrologic components controlling groundwater movement. Geologic factors include lithology and grain size variation, stratigraphic relationships, fracturing, weathering, and solutioning. Hydrologic factors include aquifer recharge, the distribution of hydraulic conductivity, the hydraulic gradient, aquifer discharge including groundwater withdrawal, and groundwater/surface water interaction. Figure 8-19 illustrates aspects of the hydrogeologic conceptual model.

The aquifer system in the quarry area is comprised of two media: limestone bedrock and alluvium. Recharge to the bedrock portion of the aquifer system occurs as precipitation which infiltrates through the soils and rock in the upland areas north of the quarry and direct precipitation and runoff into the quarry pond and exposed rock fractures. The alluvium south of the quarry is recharged by groundwater discharge from the limestone bedrock, direct precipitation, infiltration from streams (including the Missouri River), and floods. Induced infiltration from the Missouri River supplies a large percentage of the recharge to the well field south of the quarry.

Groundwater flows south and southeast in the limestone bedrock from the upland area to the alluvial floodplain. Because the bedrock discharges groundwater into the alluvium, these two media act as a continuous flow system. Aquifer tests have further demonstrated a hydraulic connection. Migration in the coarse-grained alluvium is to the east towards the Missouri River and the St. Charles County well field. The aquifer system is unconfined, although semi-confining conditions exist in the alluvium where fine-grained sediments which overlie coarser material in the floodplain are saturated.

Geologic mapping and descriptions of rock core indicate that fractures in the Kimmswick Limestone extend downward into the Decorah Group. This suggests that in the vicinity of the quarry, the Kimmswick Limestone and Decorah Group are hydraulically connected. The results of vertical coring indicate that the Plattin Limestone is massive with very little vertical or horizontal fracturing in the vicinity of the quarry. Water levels within the Plattin Limestone do not appear to correlate with measurements in the Kimmswick Limestone or the Decorah Group, suggesting the Plattin Limestone is a separate hydrostratigraphic unit in the quarry area.

Groundwater movement in the limestone units in the quarry area is predominantly controlled by the distribution of interconnected fractures. Preferential flow occurs along vertical fractures and horizontal bedding planes. Most of these features occur in the Kimmswick Limestone. Where the vertical fractures intersect bedding planes, the fractures are typically enlarged by dissolution.

Groundwater movement in the alluvium is primarily dependent upon the grain size distribution of the sediments. Lower hydraulic conductivities are associated with fine-grained overbank deposits north of the slough. Higher hydraulic conductivities, transmissivities, and well yields are associated with channel deposits including coarse sand, gravel, and cobbles in the alluvium south of the Femme Osage Slough.

Water level measurements in nested wells indicate slight differences in hydraulic head. In the alluvial aquifer north and immediately south of the slough, the hydraulic head decreases with depth indicating downward movement of groundwater. In the same area, the hydraulic head in the underlying bedrock units (Decorah Group and Plattin Limestone) is typically higher than, or equal to, the head in the overlying alluvium, indicating upward flow (discharge) from the bedrock. These two flows likely converge in coarse-grained materials at the base of the alluvium and flow laterally toward the Missouri River. South of the slough, water levels in wells screened in the fine-grained sediments are lower than those screened in coarse-grained sediments at the base of the alluvium. In this area, the hydraulic head increases with depth indicating regional discharge to the alluvium.

Interaction occurs between the Femme Osage Slough and the alluvial aquifer. Typically, the hydraulic head in the slough is higher than in the adjacent alluvium indicating leakage from the slough to groundwater. At some locations, the hydraulic head in the adjacent alluvium is higher indicating groundwater discharge into the slough.

9 GROUNDWATER QUALITY INVESTIGATIONS

This section describes the nature and extent of groundwater contamination in the vicinity of the Weldon Spring Quarry. Site-related groundwater contaminants are identified, and processes that control contaminant distribution are examined.

9.1 Previous Investigations

Groundwater quality data have been collected at the quarry since 1960 to define the nature, extent, and magnitude of radiochemical and chemical contamination. The investigations have been performed by former Government contractors, the Weldon Spring Site Remedial Action Project (WSSRAP), and several government agencies. Prior to 1987, periodic monitoring programs and special studies were undertaken. In 1987, the WSSRAP established a comprehensive groundwater monitoring program. Summaries of previous and past WSSRAP groundwater monitoring programs are provided in environmental monitoring plans and site environmental reports, which are published annually. Table H-1 in Appendix H provides a list of previous studies that relate to and support the remedial investigation.

9.1.1 Early Data (1976 - 1986)

Initial groundwater monitoring at the quarry was limited to radiological parameters. In 1976, the list of analytes was expanded to include nitrate and chloride. The early data indicated that groundwater in the bedrock surrounding the quarry was contaminated with uranium, and the highest levels were in the southeast area of the quarry. From 1979 to 1980, a study of samples from the TW-series and OB-series wells was conducted to evaluate the feasibility of utilizing specific ions as tracers of groundwater movement and to determine soil sorption properties. Only sulfate was found to correlate with the elevated uranium levels in groundwater (Ref. 30). A summary of uranium concentrations in groundwater from 1976 - 1986 is presented in Appendix H, Table H-2.

9.1.2 Post-1986 Data

When the WSSRAP began routine groundwater monitoring in 1987, the list of analytes was further expanded to include nitroaromatics (1,3,6-TNB; 1,3-DNB; 2,4,6-TNT; 2,4-DNT; 2,6-DNT; and nitrobenzene) and all major inorganic anions. The Phase I Water Quality Assessment (Ref. 74), performed in 1987, showed that Contract Laboratory Program (CLP) metals, pesticides, polychlorinated biphenyls (PCBs), and semivolatiles were not above-background and/or at detectable levels in groundwater. However, elevated levels of nitroaromatics, nitrate, sulfate, and chloride were found in wells downgradient from the quarry.

9.1.3 Groundwater Monitoring System

The groundwater monitoring system for the quarry area is shown on Figure 9-1. It consists of 45 U.S. Department of Energy (DOE) monitoring wells and four monitoring wells owned by St. Charles County. Of these wells, 19 monitor groundwater in the bedrock system (Kimmswick Limestone, Decorah Group, or Plattin Limestone). The remaining DOE wells and all county-owned monitoring and production wells are screened in the alluvium. Background wells for the bedrock system are located upgradient of the quarry. In 1992, eight monitoring wells were installed by the U.S. Geological Survey (USGS) in the Darst Bottom area, approximately 1 mi southwest of the St. Charles County well field, to establish background water quality for the alluvial aquifer.

The groundwater monitoring program for the quarry area was developed to track contaminant levels, address public concerns, and meet regulatory guidelines. The monitoring program is reviewed annually and revised periodically to respond to changes in conditions at the quarry. A major change in sampling methodology was implemented on January 1, 1995. Prior to that date, all groundwater samples were routinely collected through a 0.45 micron filter. Since then, samples have been collected unfiltered, in compliance with U.S. Environmental Protection Agency (EPA) guidance for groundwater monitoring (Ref. 15). Additional filtered samples are collected periodically for metals analyses. Studies at both the chemical plant site and the quarry have shown that the only parameters affected by filtration are a few metals (primarily aluminum, iron, and manganese) which are present in naturally occurring fine sediments and colloids. A more detailed discussion of this topic is in Appendix H. A comparison of filtered and unfiltered samples is presented in Appendix H, Table H-3.

9.2 Quarry Residuals Investigations

The quarry residuals groundwater investigations were performed in two phases. Phase I characterized the nature, extent, and magnitude of chemical and radioactive contamination in the Kimmswick Limestone, the Decorah Group, the Plattin Limestone, and the alluvium north and south of the Femme Osage Slough. These studies are listed in Appendix H (Table H-4). Background locations were also sampled during Phase I to characterize the quality of groundwater not impacted by the quarry. Where possible, sampling activities were conducted in conjunction with WSSRAP hydrogeological investigations. In a supplementary investigation, three phases of in situ groundwater sampling were performed to refine characterization of contaminant distributions in the alluvial aquifer (Ref. 57).

During Phase II, the analyte list was expanded to include carcinogenic polynuclear aromatic hydrocarbons (PAHs) and PCBs for monitoring wells that were adjacent to the quarry and had not

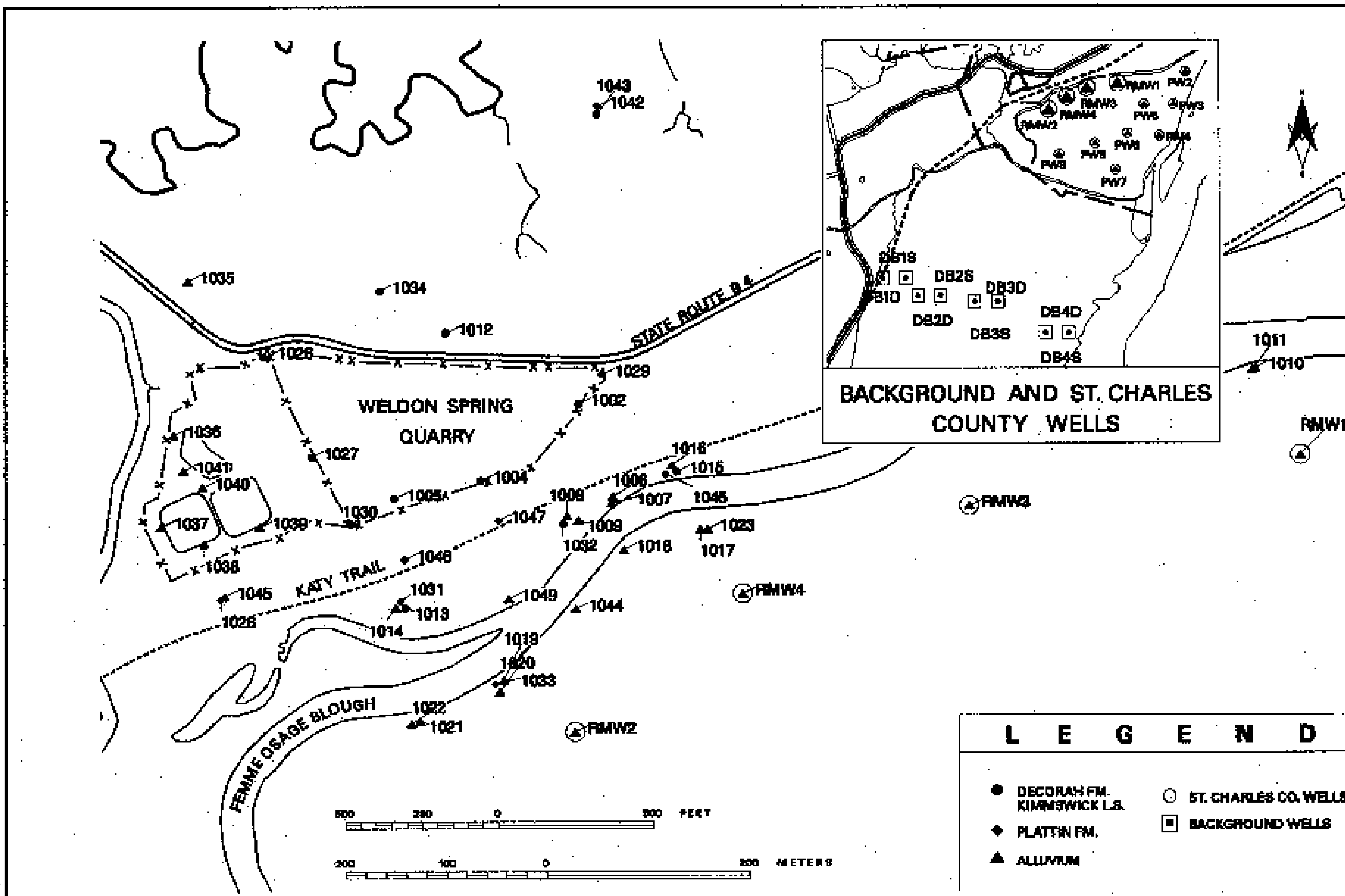


FIGURE 9-1 Locations of Background, DOE, and St. Charles County Wells

DOE/OR/21548-587

been screened for these parameters since 1990. Geochemical parameters were added to the analyte list for wells that had not been sampled for these parameters during Phase I. In addition, nitroaromatic compounds and their degradation products were monitored in selected wells to evaluate contaminant transport across the area of the Femme Osage Slough.

The chemical and radiological parameters selected for analysis during Phases I and II were based on results from previous investigations and routine groundwater monitoring. Geochemical and field parameters, such as pH, conductivity, and Eh, were also analyzed to assess contaminant mobility. These analytical parameters are listed in Appendix H, Table H-5.

9.3 Physical and Chemical Controls on Contaminant Migration

Over the 40 years during which the Weldon Spring Quarry was used as a waste disposal site, infiltrating groundwater, rainwater, and surface water mobilized contaminants from the wastes and carried them downward into the limestone bedrock. Contaminated groundwater generally migrated to the south in the bedrock and into the alluvial aquifer. The primary groundwater contaminants with sources in the quarry wastes are uranium and nitroaromatic compounds. Barium and sulfate have also been leached from the wastes and are present at elevated levels in groundwater.

Four factors have dominated migration of contaminants in the quarry groundwater system:

- the location and chemical attributes of the quarry wastes
- the hydrologic properties of the saturated bedrock and alluvium
- the geochemical characteristics of the contaminants and aquifer
- natural attenuation processes.

9.3.1 Location and Chemical Attributes of Quarry Wastes

Nitroaromatic- and uranium-bearing wastes were generally located in separate sectors of the quarry, as shown in Figure 9-2. This placement gave rise to two discrete nitroaromatic plumes, one originating from the northeast end of the quarry and the other from the west side of the quarry. The uranium-sulfate plume originated in the central area of the quarry and forms a continuous band along the southern margin of the quarry. Slightly elevated uranium concentrations have been measured at isolated locations east and south of this plume. Because the relationship of these occurrences to the main plume is not well defined, dashed lines with question marks have been used on Figure 9-2 to indicate possible extensions of the plume. The uranium-sulfate plume overlaps the southern margins of the nitroaromatic plumes; thus, some wells show elevated levels of both groups of contaminants.

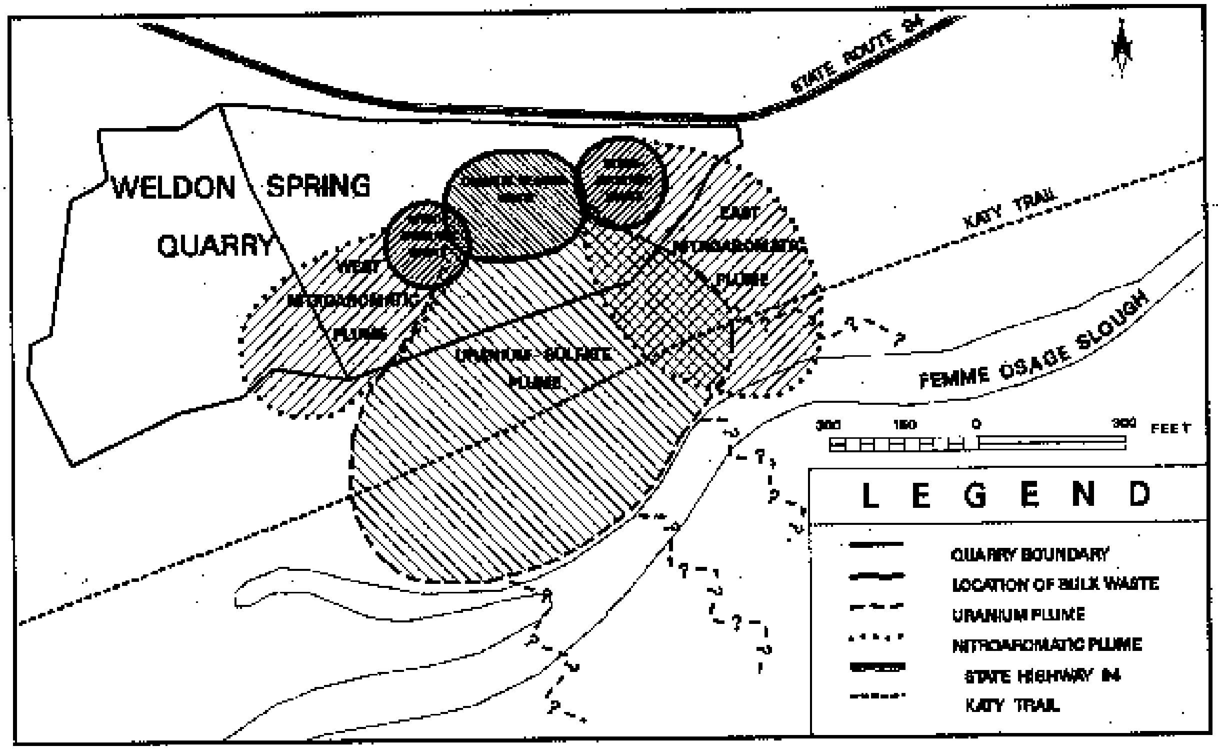


FIGURE 9-2 Schematic Presentation of Quarry Waste Locations and Resulting Groundwater Plumes

9.3.2 Hydrologic Controls on Contaminant Distribution

Advection and dispersion are the primary hydrologic processes controlling the rate and direction of contaminant migration. Hydrologic controls are further discussed in Section 8 and are discussed in relation to the chemical nature of the system in Section 10.

9.3.3 Geochemical Characteristics of Contaminants and the Aquifer

The geochemical characteristics of the contaminants and the aquifers also affect the nature and extent of contamination. Only contaminants that are readily leached from the wastes by infiltrating rain, surface water, or groundwater enter the groundwater system. Some insoluble contaminants, such as radium and thorium, that were heavily concentrated in the bulk wastes, rarely have been detected in monitoring wells.

In the quarry area, the major element chemistry of the bedrock and alluvial aquifers groundwater is dominated by calcium and bicarbonate ions. This is illustrated with a Piper diagram (Figure 9-3), which shows all locations clustering in the calcium-bicarbonate region.

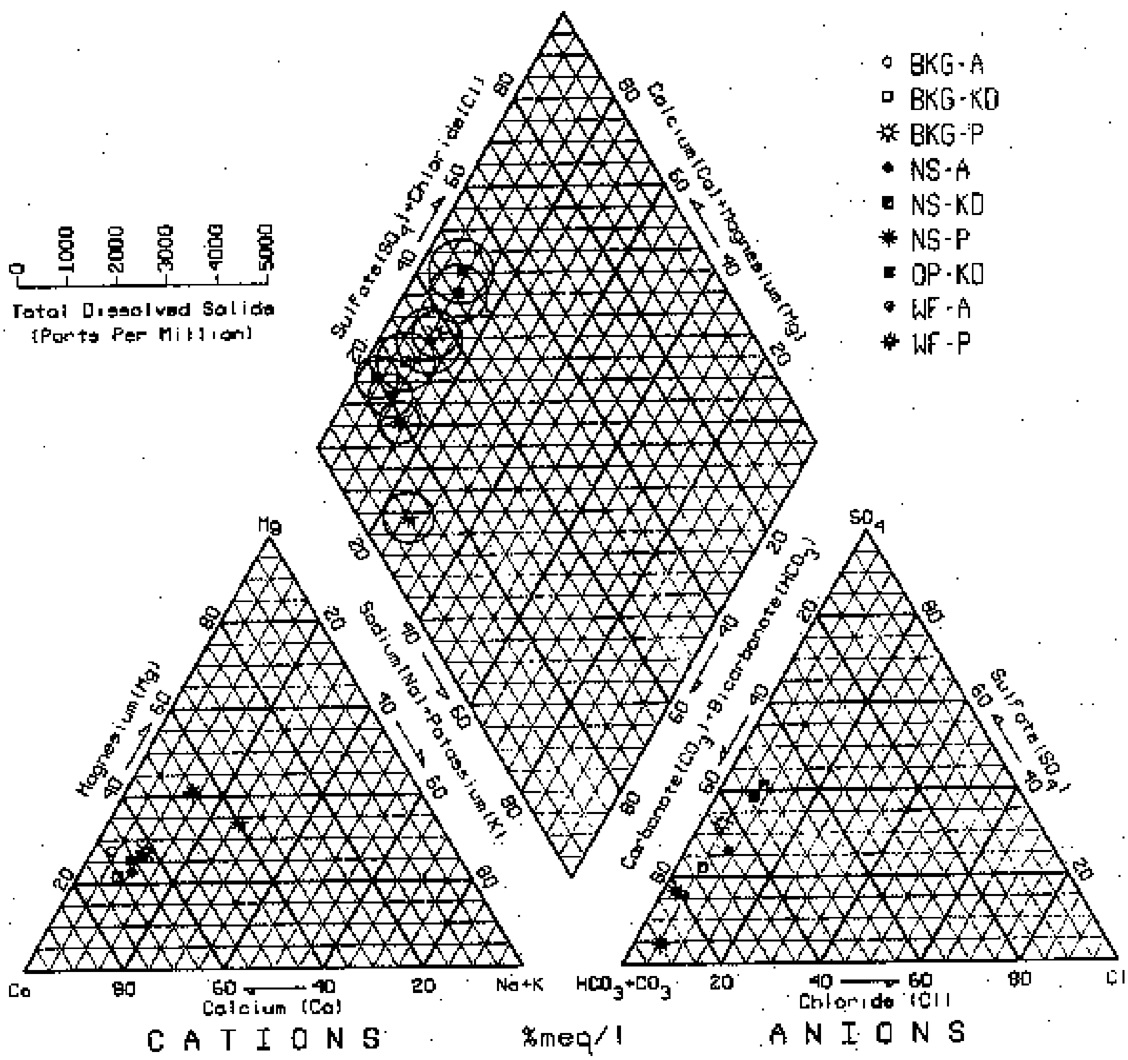
Although all groundwater within the quarry area is of the same general type (calcium-bicarbonate), the concentrations of minor and trace constituents vary considerably. These variations are due primarily to the oxidation potential of the aquifer.

In the alluvial aquifer, the natural causes of chemical variability are the oxidation potential of the aquifer, the organic content of the aquifer, and the degree of hydraulic connection with the Missouri River and/or the calcium carbonate bedrock aquifers. The oxidation potential is shown on Figure 9-4, which maps Eh isopleths for the alluvial aquifer. Areas with negative Eh values are at lower (i.e., more reducing) oxidation potentials than areas with positive values.

Oxidation-reduction reactions are important processes for soils that are periodically inundated with rain or flood water (Ref. 67, 68), such as the soils in the floodplain of the Missouri River. Under favorable conditions, which include near neutral pH, available organic material, and temperatures suitable for microbial activity, water-saturated soils become oxygen-depleted within a few millimeters of the water-air interface. Within a few days of inundation, free oxygen is consumed, and reduction of other compounds (e.g., manganese and iron oxides/hydroxides, sulfate, and other oxidized compounds) begins (Ref. 67). These conditions occur in the saturated alluvial soils south of the slough and in the Darst Bottoms, where Eh values range from -10 to -229 mV. In this area, iron and manganese, which are released to groundwater as soil reduction proceeds, are present at high concentrations in the groundwater.

Although saturated soils and conditions favorable for reduction reactions are also present north of the slough, oxidation potentials in this area are high (Eh values 0 to 277 mV) relative to the area south of the slough. Exceptions to this observation occur at two monitoring wells (MW-1007 and MW-1009) that are located near the north bank of the slough in tight clays. Groundwater north of the slough exhibits high sulfate and low iron and manganese levels. The latter elements are sequestered in insoluble oxides and hydroxides. Elevated levels of iron and manganese, which that have been measured in some groundwater samples from this area, are attributed to inclusion of Fe-Mn colloidal material.

The absence of reducing conditions in the saturated, organic-rich alluvium north of the slough may have an anthropogenic origin. Oxidation of the soils in this area may result from mining of the quarry, which opened additional pathways for oxidized water to directly infiltrate the aquifer. In addition, migration of soluble oxidized species (i.e., sulfate and nitroaromatic compounds) from quarry wastes also may have supplied oxygen to the aquifer. Near the Femme Osage Slough, oxidized conditions abruptly give way to reducing conditions, defining a reduction front along the low-lying, poorly drained area adjacent to the slough.



BKG-A = Background Alluvium
BKG-KD = Background, Kimmswick Limestone/Decorah Formation
BKG-P = Background, Plattin Limestone
NS-A = Alluvium North of Slough
NS-KD = Kimmswick/Decorah North of Slough
NS-P = Plattin North of Slough
OP-KD = Kimmswick/Decorah in Quarry Proper
WF-A = Alluvium in Well Field
WF-P = Plattin in Well Field

FIGURE 9-3 Piper Diagram for Quarry Vicinity Groundwater

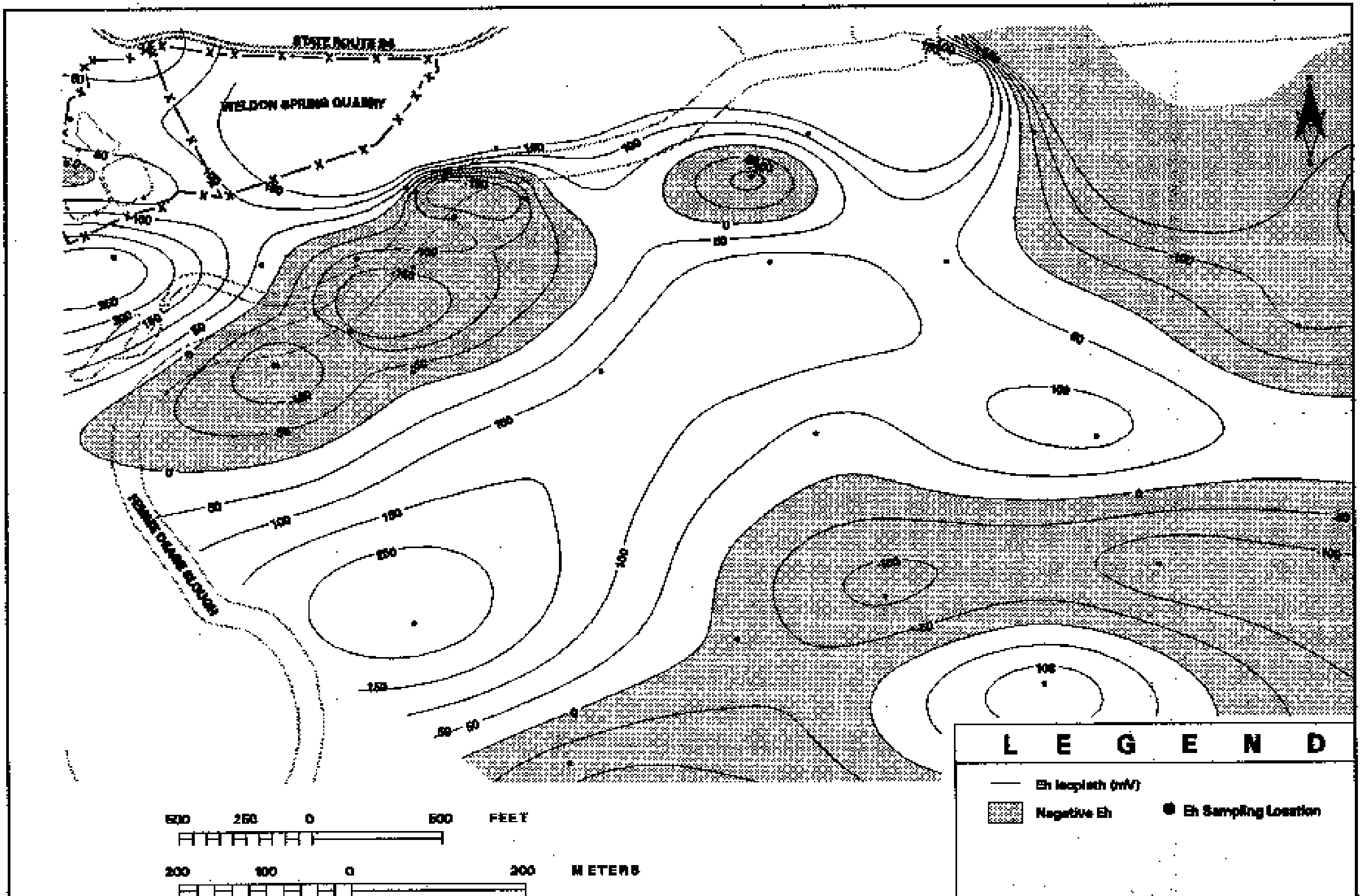


FIGURE 9-4 Eh Isopleths for the Alluvial Aquifer

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Groundwater chemistry in the shallow bedrock aquifer is controlled by oxidation potential and residence time in the aquifer. Equilibrium with the calcium carbonate host rocks, which is a function of residence time and the degree of mixing with surface water, strongly influences the groundwater chemistry, especially alkalinity, pH, and calcium content. Near the quarry, the shallow bedrock aquifer is relatively oxidized, exhibiting high sulfate and low iron and manganese levels. Bedrock groundwater also displays positive Eh values, with the Kimmswick Limestone and Decorah Group being more oxidized (median Eh value = 133 mV) than the underlying Plattin Limestone (median Eh value = 38 mV). Reduced oxygen potentials are only observed at deeper levels in the Plattin Limestone. In comparison to the alluvial aquifer, organic material and microbial organisms are not abundant in the shallow bedrock aquifer, thus reduction reactions occur very slowly.

9.3.4 Natural Attenuation Processes

Reactions along groundwater migration pathways influence the mobility of dissolved contaminants. In the quarry aquifer system, contaminants are attenuated by one or more of the following processes: sorption, biodegradation, and/or precipitation.

9.3.4.1 Sorption. Attenuation of contaminants via sorption is a significant process in fine-grained soils containing abundant organic material such as are present in the alluvial aquifer. Sorption is simplistically described by a linear sorption isotherm if there is a linear relationship between the amount of solute sorbed onto the solid and the concentration of the solute. In this case, the solute is retarded in proportion to the distribution coefficient (Kd), which is the slope of the line relating the concentration in liquid and solid phases. Linear sorption isotherms are shown in Figure 9-5 for a range of Kd values. Kd values are typically developed from experimental data and are specific to a given constituent in relation to a particular solid. Site-specific experimental data provide the most reliable Kds.

Higher Kd values indicate higher degrees of sorption; however, these reactions are limited by the number of available sorption sites (i.e., the sorption capacity of solid materials). In the case of uranium, which is expected to be soluble as an anionic carbonate complex (Ref. 61) sorption sites are limited to Fe-Mn oxides and edges of clay minerals (Ref. 67). When all sites are saturated (i.e., the sorption capacity is exhausted), contaminant concentrations are no longer attenuated as groundwater moves through the aquifer.

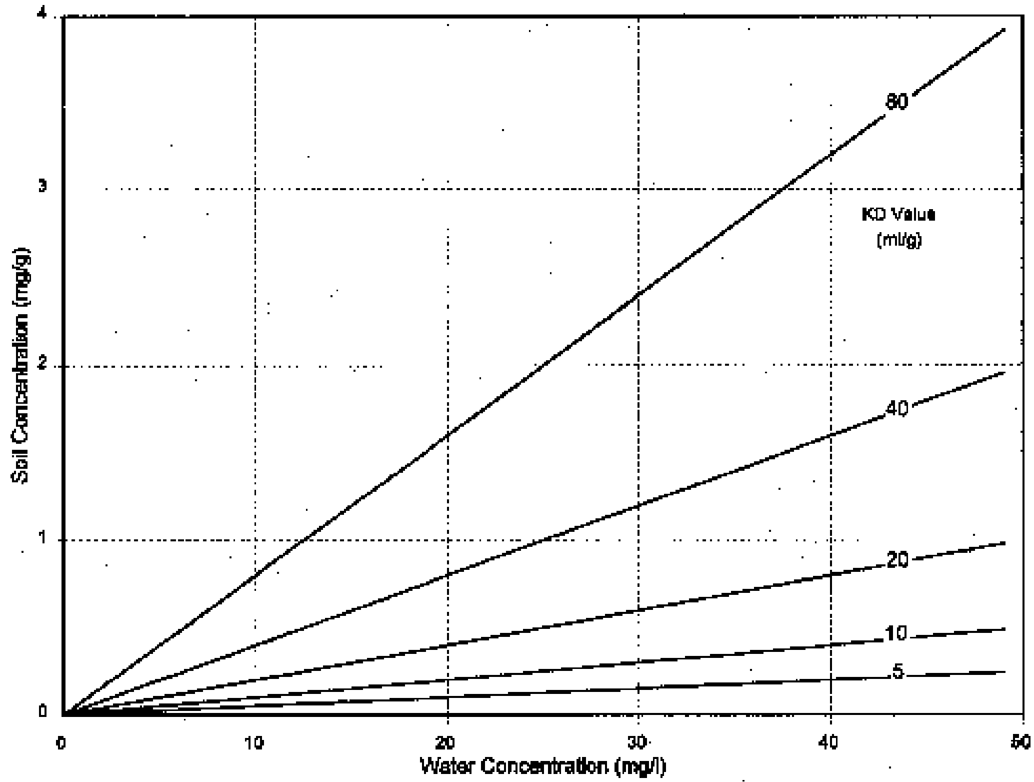

FIGURE 9-5 Equilibrium Uranium Concentrations in Soil and Groundwater for a Range of Kd Values

A summary of distribution coefficients that have been used for the quarry vicinity is presented in Table 9-1. Site-specific distribution coefficients have not been determined for any quarry aquifers. Berkeley Geosciences (Ref. 30) has presented sorption coefficients which were derived from literature for rock and soil; however, the actual distribution coefficients were not presented in the report. The alluvial sorption coefficient of 3.6 translates to a distribution coefficient between 1 and 2. This value probably is unrealistically low for the alluvium, which contains abundant organic matter (Ref. 58). The U.S. Geological Survey (USGS) also determined distribution coefficients for soils at the nearby Weldon Spring Chemical Plant (Ref. 32). These distribution coefficients are more likely representative of the upland soils blanketing the quarry than of the alluvium.

TABLE 9-1 Uranium Sorption and Distribution Coefficients

MATERIAL	DISTRIBUTION COEFFICIENT (ml/g)	SORPTION COEFFICIENT*	REFERENCE
Fractured Limestone	0.024	1.1	(Ref. 30)
Alluvium	1.1	3.6	(Ref. 30)
Clay	6.9	36.4	(Ref. 30)
Vicinity upland soils	10.7 - 437	--	(Ref. 47)

* Sorption coefficients (a) were derived using the following equation (Ref. 30):

$a = Kd\ Pb/1\text{-}\theta$

where:

Pb = bulk density

θ = porosity

Kd = distribution coefficient

9.3.4.2 **Biodegradation.** Biological reactions can also reduce contaminant concentrations in the groundwater. These reactions are particularly important for organic compounds, which are transformed to other species or mineralized to CO_2. Studies performed on materials collected from the former Weldon Spring Ordnance Works have shown that under favorable conditions, biological processes readily breakdown nitroaromatic compounds, which are the only organic contaminants detected in the groundwater at the quarry (Ref. 59). Biodegradation occurs primarily in the alluvial sediments, which are rich in organic material and microbes.

9.3.4.3 **Precipitation of Solid Phases.** Removal of contaminants from groundwater via precipitation of solid phases typically results from changes in geochemical conditions, which cause one or more contaminants to exceed their solubility limit in water.

Oxidation-reduction (redox) reactions control the solubility and mobility of major contaminants (sulfate, arsenic, and uranium) in alluvial and bedrock aquifers adjacent to the quarry. Like iron and manganese, arsenic is soluble under reducing conditions and precipitates with these metals under oxidizing conditions. In contrast, sulfate and uranium are soluble under oxidizing conditions and precipitate in solid phases under reducing conditions (Refs. 60 and 61).

9.4 Nature and Extent of Contamination

Analytical data from previous and recent investigations were evaluated to determine the nature and extent of contamination in groundwater near the quarry. In addition, concentrations of constituents that occur naturally in groundwater were also established from data collected for these investigations. Quarry groundwater data collected from 1987 to July 31, 1996, are summarized in Table H-6 through H-8 of Appendix H.

9.4.1 Data Groups

Summary statistics are calculated for data groups, which are based on geographic location and lithologic unit. Some groups encompass both contaminated and uncontaminated sample locations. Subgroups are examined if significant contamination is present at a number of locations within a group. Groundwater data groups are:

<u>Alluvium</u>

- BKG-A Background
- NS-A North of slough
- QP-A Quarry proper
- WF-A Well field[a]

<u>Kimmswick Limestone/Decorah Groups</u>[b]

- BKG-KD Background
- NS-KD North of slough
- QP-KD Quarry proper

<u>Plattin Limestone</u>

- BKG-P Background
- NS-P North of slough
- WF-P Well field[a]

(a) Well field area is bounded by the Femme Osage Slough to the north and the Missouri River to the south and east.

(b) The Kimmswick Limestone and Decorah Group are not present beneath the Femme Osage Slough as shown in Figures 8-2 and 8-3.

9.4.2 Background

Natural (background) groundwater chemistry in the alluvial and bedrock aquifers near the quarry was determined at the upgradient sampling locations shown on Figure 9-1. These locations were sampled for naturally occurring parameters, including inorganic anions, metals, radionuclides, and miscellaneous geochemical parameters (Table H-5). Background data and study area data are summarized in Tables H-6 through H-8 of Appendix H. The upper 95% confidence limit about the mean for derived background ($UCL95_B$) values for each of the background groups is shown in Figures 9-6A, B, and C.

9.4.3 Identification of Contaminants

Following the definitions given in Section 3, the background comparisons shown in Figures 9-6A through 9-6C indicate that a number of naturally occurring parameters significantly exceed the derived background levels (>2 times background). In the shallow aquifer (alluvium-Kimmswick Limestone/Decorah Group), these parameters include three anions (bromide, chloride and sulfate), 14 metals (aluminum, arsenic, chromium, cobalt, copper, iron, manganese, mercury, nickel, potassium, sodium, thallium, vanadium, and zinc), two miscellaneous parameters (organic carbon and phosphorous), three radionuclides (Rn-222, Th-230, and total uranium), and gross alpha and gross beta. Significantly elevated parameters in the Plattin Limestone include five metals (barium, cadmium, calcium, manganese, and mercury) and two radionuclides (Rn-222 and total uranium). With the exception of sulfate, sodium, calcium, and potassium, these parameters are trace constituents in groundwater.

Maximum nitroaromatic compound concentrations measured in groundwater during 1995-1996 are given in Figure 9-6D. Elevated levels of nitroaromatic compounds occur in the alluvium and shallow bedrock north of the slough.

Of the identified contaminants, uranium, gross alpha, nitroaromatic compounds (2,4-DNT and 2,4,6-TNT), and thallium exceed primary water quality standards; iron, manganese, and aluminum exceed secondary standards (as given in Section 3); and antimony exceeds EPA health advisory levels. Locations where these elevated levels occur are identified in Table 9-2. Contaminants that exceed primary water quality standards are the major concern in quarry vicinity groundwater. These contaminants, plus sulfate and arsenic, form the basis for discussion of nature and extent of contamination.

Sulfate is included because, on a well-by-well case, it exceeds water quality standards north of the slough, its geochemical characteristics are similar to those of uranium, and its concentration is an indicator for the oxidation potential of the aquifer. Arsenic is included because it is consistently above water quality standards in wells located adjacent to the south side of the slough. To avoid redundancy, gross alpha, which reflect the activity of all radionuclides that emit alpha particles, is not carried forward in the following discussions because concentrations are primarily controlled by uranium levels in groundwater.

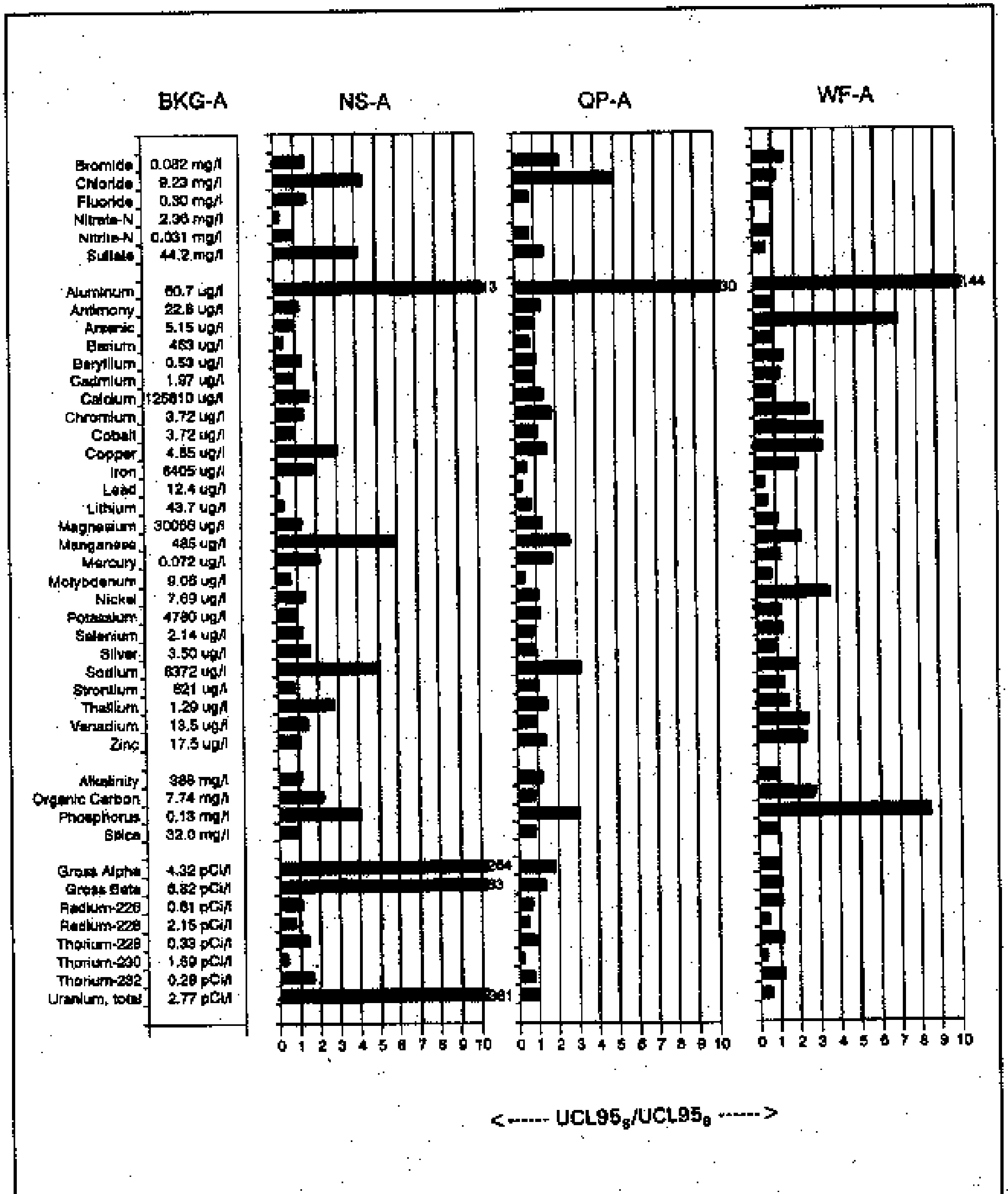

FIGURE 9-6A Groundwater: Background Comparison for Naturally Occurring Parameters in Alluvium

The bar graphs display the UCL95 value for each data group ($UCL95_S$) divided by the UCL95 value for background ($UCL95_B$). Values greater than 2 indicate significant deviation from background (Section 3). Note: Rate set to 1 if 100% of sample data were below the limit of detection.

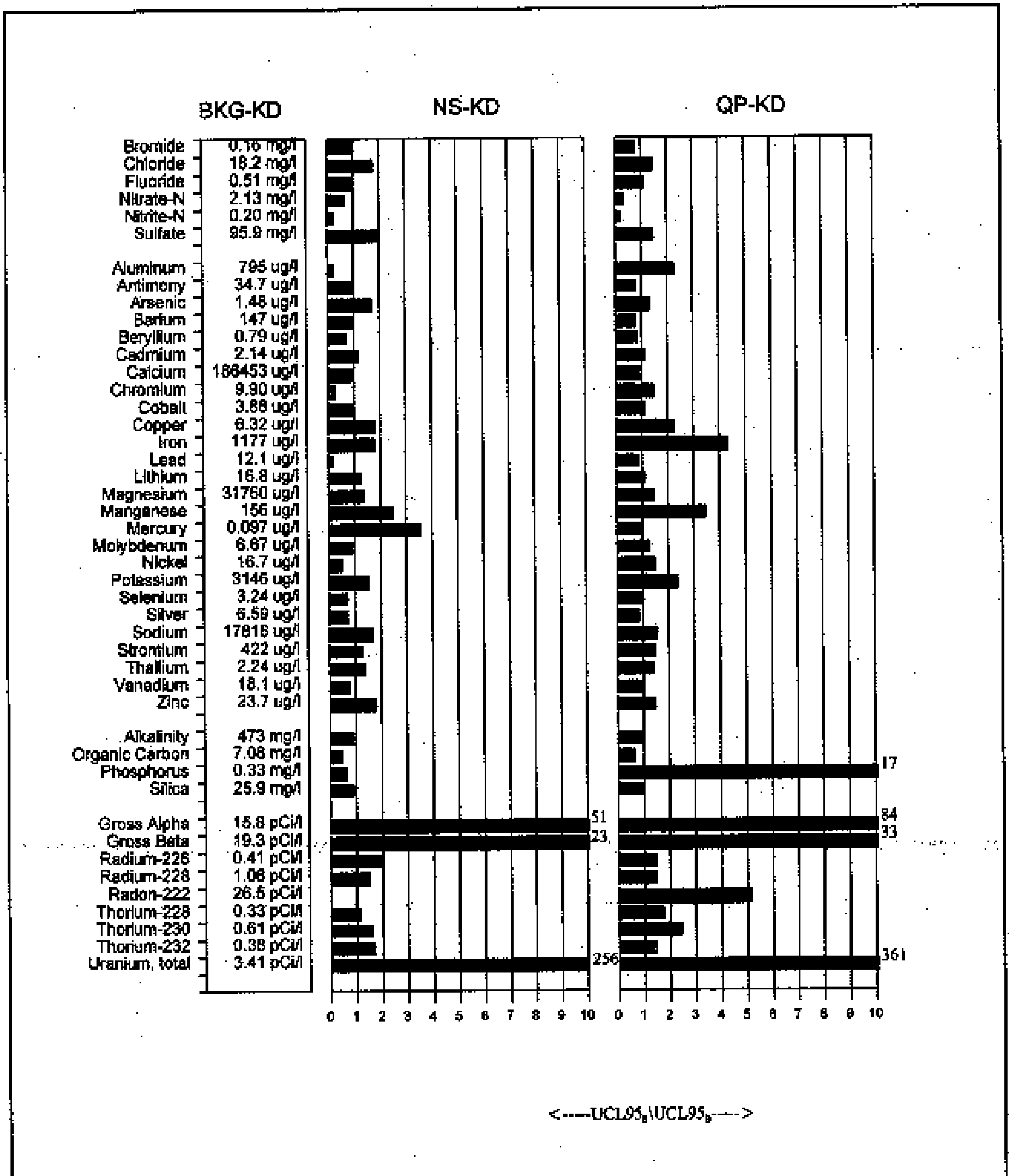

FIGURE 9-6B Groundwater: Background Comparison for Naturally Occurring Parameters in Kimmswick Limestone/Decorah Group

The bar graphs display the UCL95 value for each data group ($UCL95_g$) divided by the UCL95 value for background ($UCL95_b$). Values greater than 2 indicate significant deviation from background (Section 3) Note: Rate set to 1 if 100% of sample data were below the limit of detection.

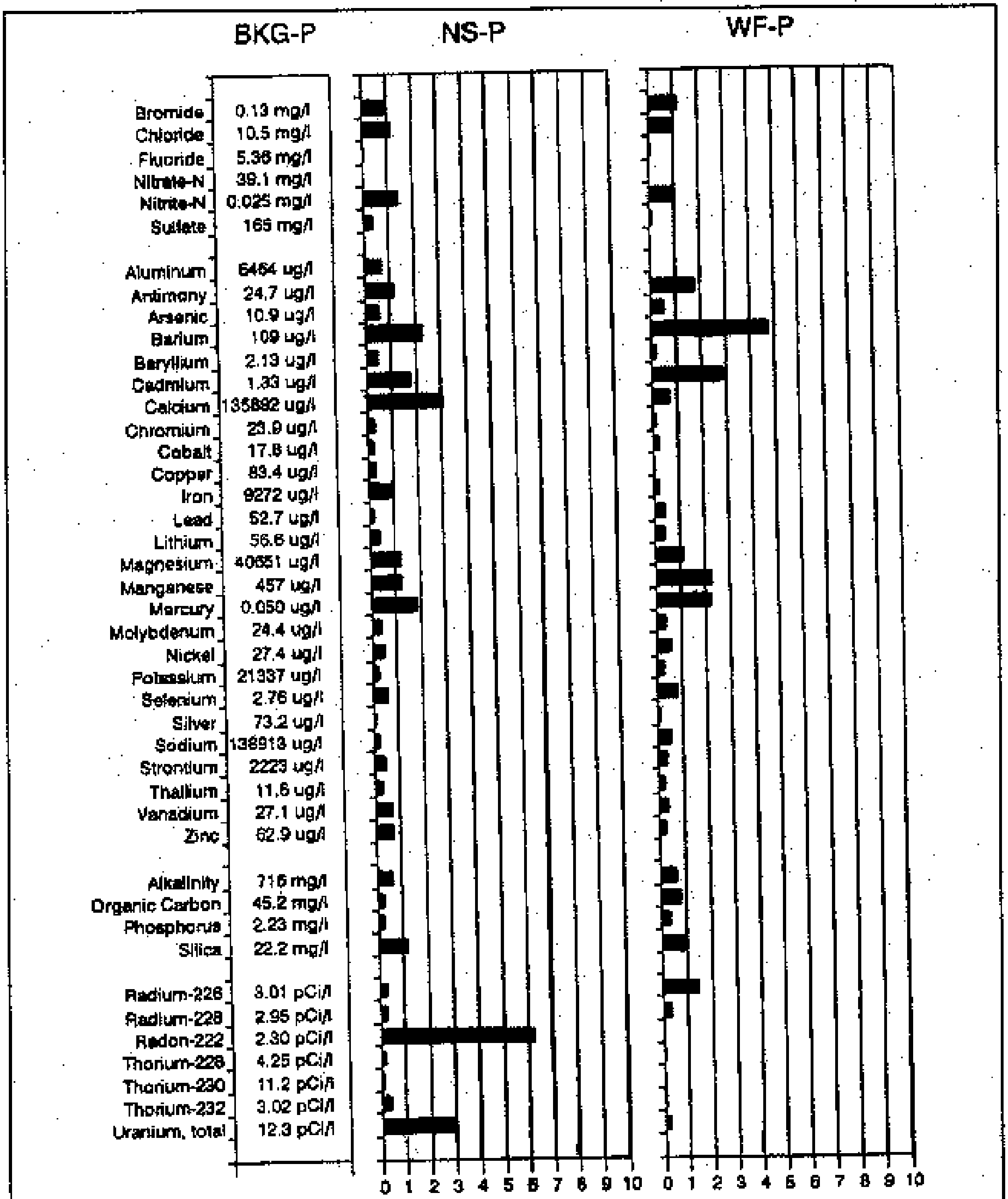

FIGURE 9-6C Groundwater: Background Comparison for Naturally Occurring Parameters in Plattin Limestone

The bar graphs display the UCL95 value for each data group ($UCL95_S$) divided by the UCL95 value for background ($UCL95_B$). Values greater than 2 indicate significant deviation from background (Section 3) Note: Rate set to 1 if 100% of sample data were below the limit of detection.

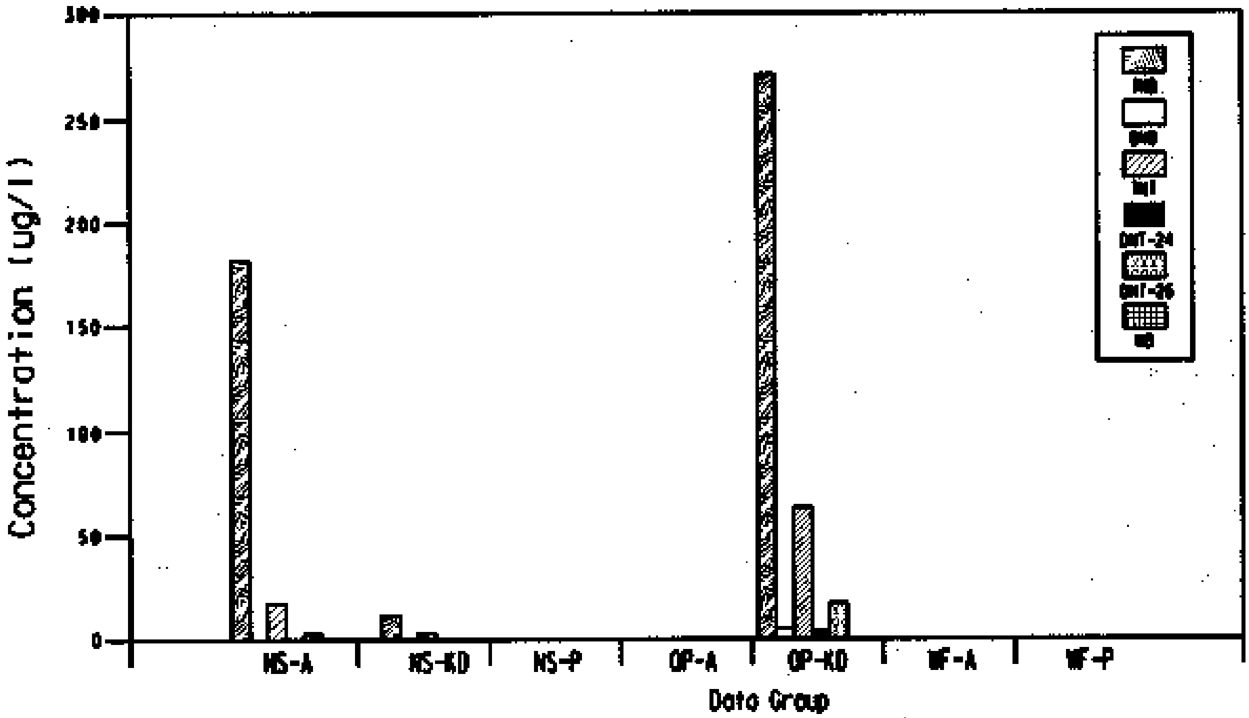

FIGURE 9-6D Groundwater: Maximum Nitroaromatic Compound Concentrations for 1995-1996

TABLE 9-2 Areas Where Contaminants Exceed Water Quality Standards

CONTAMINANT (STANDARD)	NS-A	NS-KD	NS-P	QP-A	QP-KD	WF-A	WF-P
Primary Standards							
Gross Alpha (15 pCi/l)	X	X			X		
Uranium (13.6 pCi/l)	X	X			X		
DNT-24 (0.11 μg/l)	X	X			X		
Arsenic (50 μg/l)						X*	
Thallium (2 μg/l)	X	X	X		X		X
Secondary Standards							
Aluminum (200 μg/l)	X			X	X	X	
Manganese (50 μg/l)	X	X	X	X	X	X	X
Sulfate (250 mg/l)	X*	X*			X*		

*Indicates localized area of significant contamination within data grouping

Antimony and thallium values, which exceed water quality standards at background and potentially impacted locations, appear to be an artifact of the CLP prescribed method used to analyze these samples. For antimony, this method yielded a detection limit of 60 μg/l, which is 10 times the maximum contaminant level (MCL) of 6 μg/l. Samples collected more recently have been analyzed by a method that has detection limits below the MCL. These data (identified as Antimony* in Table H-6) indicate antimony only exceeds the MCL in the NS-KD and the WF-P sample groups, although the sample size is limited. Detection limits for thallium were varied, but typically were greater than 20 μg/l, which is 10 times the MCL of 2 μg/l. Additional samples will be collected and analyzed for both antimony and thallium to determine whether levels exceed MCLs.

9.5 Distribution and Sources of Primary Contaminants

Although a large volume of contaminated material was present in the quarry from 1941 until mid-1995, the extent of groundwater contamination has remained relatively constant since the WSSRAP began monitoring in 1987. Although the extent has remained relatively constant, contaminant concentrations have varied widely during the 9.5 year monitoring period. This variation probably results in large part from bulk waste construction and removal activities, which disturbed the waste and exposed fresh surfaces to leaching. As shown in Figure 9-7, disturbance of the waste began in 1991 with the construction of the quarry water treatment plant and ended in late 1995 with final removal activities. Contaminant levels have also been influenced by the dramatic fluctuation in groundwater levels during the 1987-1996 monitoring period, which included three major floods.

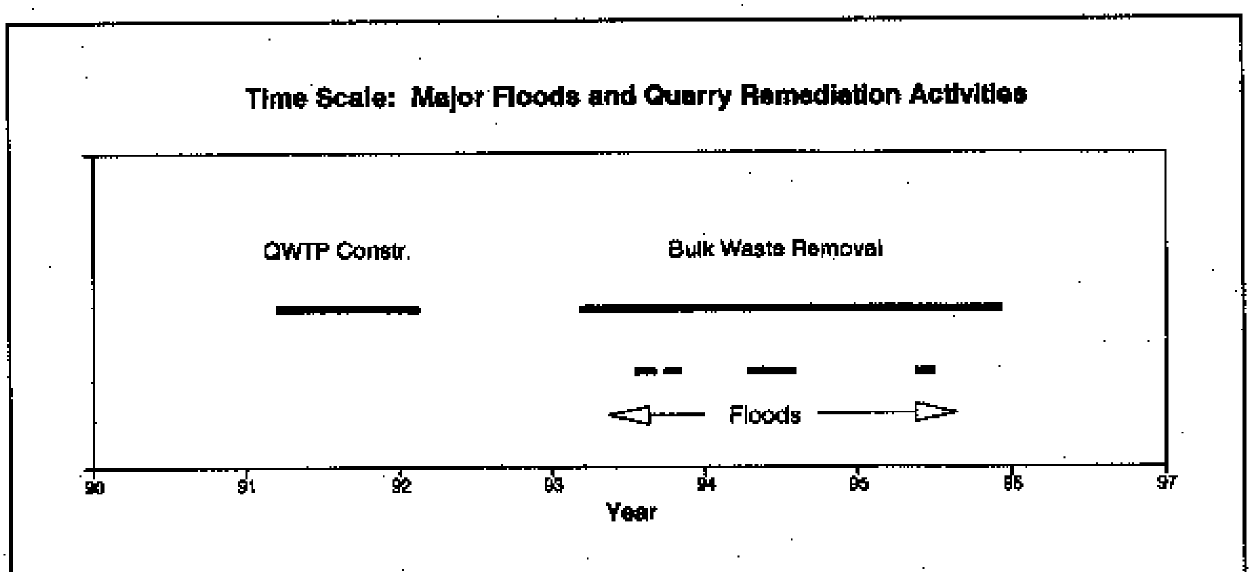

FIGURE 9-7 Chronology of Events that Impacted Groundwater Near the Quarry

The groundwater distribution of uranium, nitroaromatic compounds, thallium, sulfate, and arsenic are discussed in the following sections. Not all of these contaminants are related to quarry sources. Other potential contaminant sources are also evaluated.

9.5.1 Nitroaromatic Compounds

Nitroaromatic compounds detected in groundwater are derived from waste and debris that were removed from the former Weldon Spring Ordnance Works and stored in the quarry. In addition to trinitrotoluene (TNT) and dinitrotoluene (DNT), this waste includes a series of production by-products and degradation compounds. During 9.5 years of monitoring, six wells have yielded groundwater contaminated with one or more nitroaromatic compound in excess of 0.1 ppb. Four were shallow bedrock wells, and two were alluvial wells. The highest concentrations of total nitroaromatic compounds have occurred in MW-1002, a bedrock well on the eastern rim of the quarry, and in MW-1006, an alluvial well located east-southeast of the quarry (Figure 9-1). A separate area of contamination extends from the western margin of the quarry where nitroaromatic compounds (in excess of 0.1 ppb) are found in one alluvial well and four shallow bedrock wells. As in the eastern plume, the highest concentrations occur in a bedrock well (MW-1027) close to the quarry proper.

Nitroaromatic compounds have not been detected south of the slough; however, nitroaromatic compounds analyzed during the routine monitoring are primarily oxidized compounds. These compounds could be degraded to more reduced species near the Femme Osage Slough and migrate, undetected, into the well field. A special study was conducted to examine a suite of nitroaromatic degradation compounds (reduced species) at monitoring locations south of the slough. Like the primary suite of compounds analyzed by the WSSRAP, these degradation compounds were also below the limit of detection. Coupled with previous monitoring data, the results indicate that the nitroaromatic contamination is confined to the north side of the slough. Figure 9-8 shows concentrations and the distribution of nitroaromatic compounds for the post-remediation period (1995-1996).

Nitroaromatic compounds 2,4,6-TNT and 2,6-DNT are generally found in bedrock and alluvium on the east side of the quarry proper and in a portion of the downgradient alluvium. A western area of nitroaromatic contamination is evident in Figure 9-8, where 2,4-DNT is measured primarily in one Kimmswick-Decorah well (MW-1027). The distribution and fate of nitroaromatics in the quarry groundwater are controlled by the location of the source (see Figure 9-2), groundwater flow direction and gradient (see Figure 8-7), and attenuation processes acting on the contaminants. Although relatively soluble in water, these compounds are particularly susceptible to various transformation processes and are likely confined to the north side of the slough primarily by a combination of biodegradation and redox reactions. Transfer and transport processes such as sorption and advection/dispersion also play a role in the distribution of the compounds.

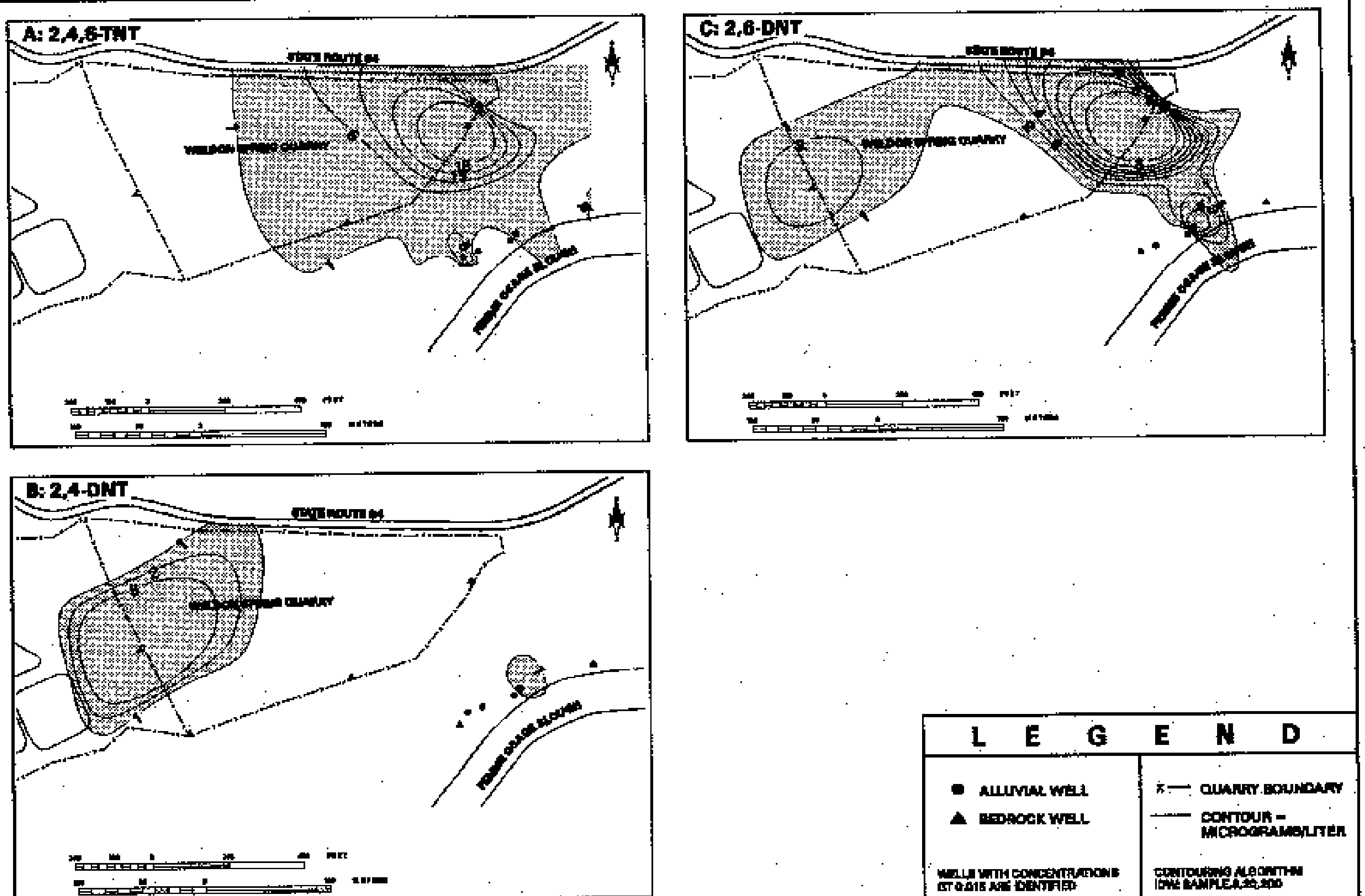

FIGURE 9-8 Groundwater: Isopleths for Nitroaromatic Compounds, Based on Average Values for 1995-1996 Monitoring Period

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Microbial degradation is probably the most important of the processes which break down nitroaromatic compounds and is enhanced by the increase of organic material in alluvium adjacent to the slough and Little Femme Osage Creek. Reducing conditions near the slough provide lower oxidation potentials to enhance the degradation of the compounds.

At the start of the bulk waste construction activities, concentrations of nitroaromatic compounds increased sharply in most monitoring wells where these compounds had previously been detected. Figure 9-9A shows the trend for TNT in selected wells monitoring in the eastern plume, and Figure 9-9B shows the trend in MW-1027. As remediation progressed, concentrations began to decrease, and by early 1996 were below pre-1991 levels in all wells except MW-1002 (Figure 9-9A). The rapid decline after waste removal indicates that sorption of nitroaromatic compounds onto aquifer solids probably is not significant. The persistence of low levels of these compounds likely represents residual contaminated groundwater that is being flushed from pore spaces and small fractures. The rate that concentrations of these compounds is decreasing appears to be related to the lithology of the aquifer. Wells screened in alluvial materials showed a faster rate of decrease than those screened in the bedrock. This difference likely results from the increased rate of microbial degradation in the alluvium. If this hypothesis is correct, concentrations of nitroaromatic compounds should continue to decrease more rapidly in the alluvial aquifer than in the bedrock aquifers.

9.5.2 Sulfate

Sulfate is a soluble sulfur-oxygen anionic complex that is stable in oxidizing conditions. Sulfate sorption on aquifer solids is not a significant process, but precipitation as barium sulfate ($BaSO_4$) limits dissolved concentrations. Because barium is a common trace constituent of quarry aquifers, sulfate levels rarely exceed 600 mg/l, even north of the slough where the highest levels are found.

The sulfate anion is not stable under reducing conditions as shown in Figure 9-10 which compares sulfate concentrations with Eh values. Under these conditions, the oxidation state of sulfur decreases from 4^+ to 2^-, and the sulfide ion becomes the stable form of sulfur. This ion forms insoluble phases with a number of readily available metals, resulting in extremely low sulfide concentrations in groundwater. Sulfide has not been measured routinely at the quarry; however, its presence can be inferred by absence or extremely low levels of sulfate.

Contrary to the expected relationship with the redox state of the aquifer, a few monitoring locations have yielded groundwater with elevated sulfate levels and low Eh values. This relationship reflects non-equilibrium conditions and probably results from mixing sulfate-rich oxygenated water with oxygen-poor, reduced water. This mixing may occur locally in the aquifer or during sampling if a monitoring well is screened across layers with differing oxidation potentials.

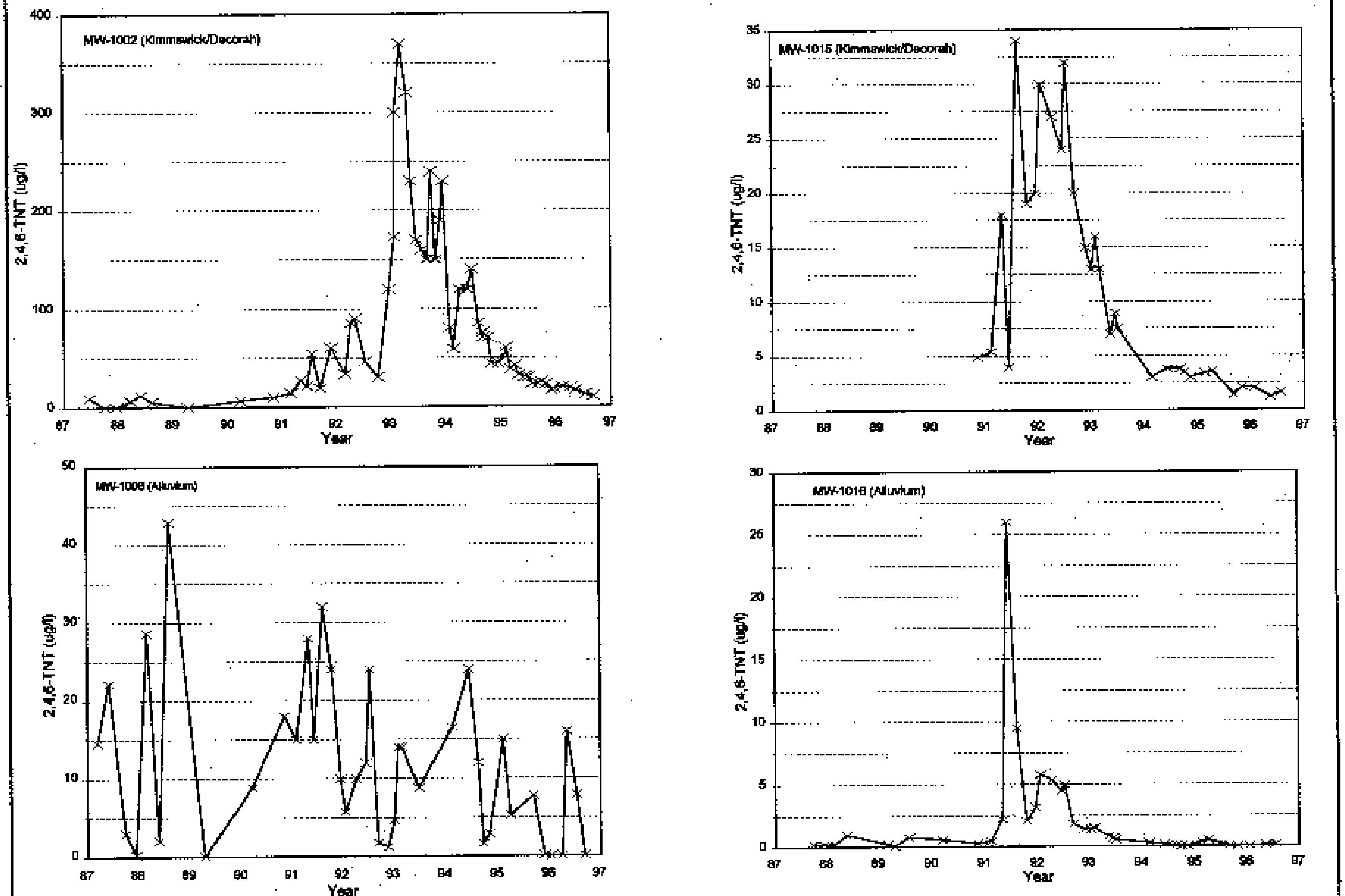

FIGURE 9-9A Historic 2,4,6-TNT Levels at Selected Monitoring Wells in the Eastern Plume

Note: Different scales used in figures

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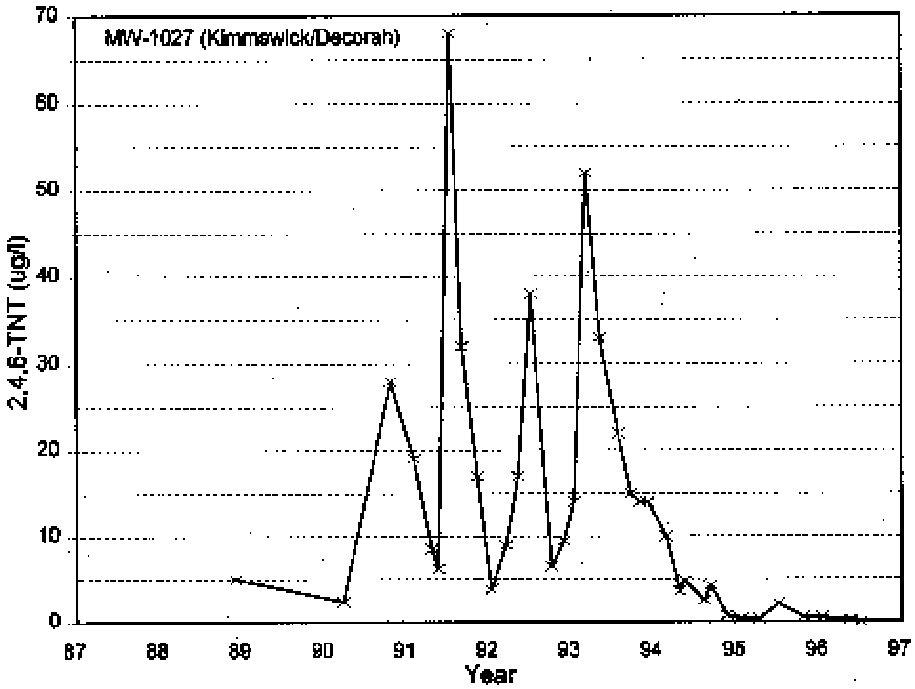


FIGURE 9-9B Historic 2,4,6-TNT Levels at Bedrock Monitoring Well MW-1027

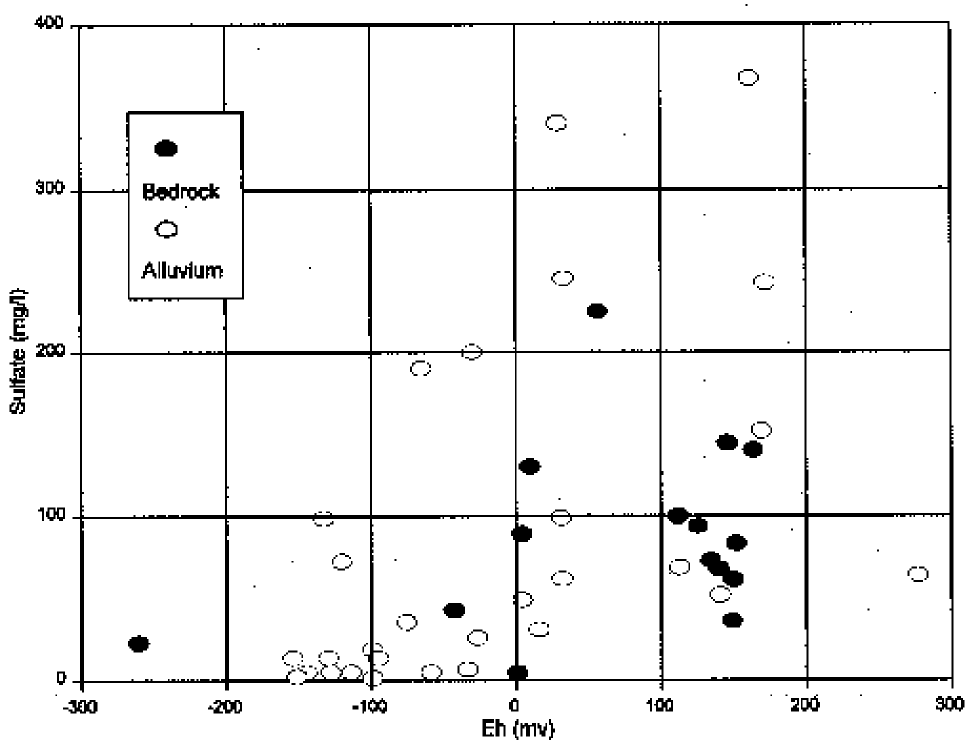


FIGURE 9-10 Groundwater: Comparison of Sulfate and Eh Values

North of the Femme Osage slough, sulfate levels are lower in the Plattin Limestone than in the alluvium, Kimmswick Limestone, and Decorah Group. This relationship may indicate that sulfur content or the oxidation potential of the Plattin Limestone is lower than the other units. Elevated sulfate levels are usually associated with elevated levels of uranium, which respond similarly to the oxidation potential of the aquifer. This relationship is shown in Figure 9-11. Although uranium and sulfate are soluble as anionic complexes, uranium is more strongly sorbed on solids, especially those present in the alluvial aquifer. Thus, sulfate and uranium levels do not form a linear trend in Figure 9-11.

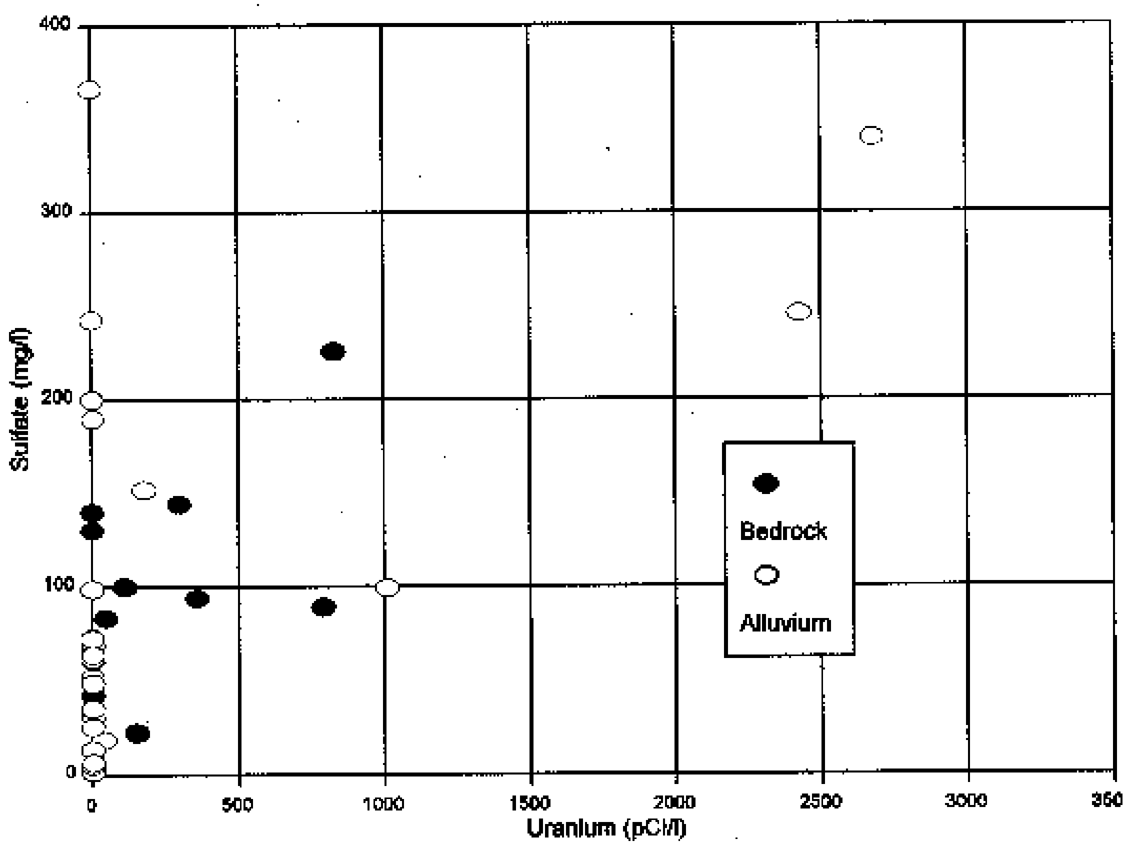


FIGURE 9-11 Groundwater: Comparison of Sulfate and Uranium Activity

Bulk waste is the probable source of elevated sulfate concentrations that occur north of the Femme Osage Slough. However, it is also possible that some sulfate is formed from oxidation of sulfides in the aquifer. Although sulfate levels did respond to waste-removal activities, the increases and decreases were not as dramatic as those of the nitroaromatic compounds, indicating that other, possibly natural, sources of sulfate may be present in the aquifer.

9.5.3 Uranium

Uranium is the major quarry-related groundwater contaminant. It is the only radiological constituent of the bulk waste materials that is readily dissolved in groundwater. Like sulfate, uranium is soluble under oxidizing conditions but precipitates in a number of insoluble phases under reducing conditions (Refs. 60 and 61). In bicarbonate-type groundwater, which is present in both the saturated bedrock and alluvium, uranium is soluble as an anionic carbonate complex. Levels of dissolved uranium do not show a direct correlation with carbonate alkalinity, however. Unlike sulfate, uranium is sorbed onto solid materials, especially iron-manganese oxides and organic matter (Ref. 62) as observed in soil borings south of the quarry. The affinity of uranium for organic matter was also qualitatively observed during remediation of the shallow soils in the vicinity property directly south of the quarry. During this action, the highest levels of uranium were found associated with tree roots and in a dark soil layer that appeared to be rich in organic material.

Uranium-contaminated groundwater forms a plume that migrates from the southern margin of the quarry and extends generally southward and eastward, as shown in Figure 9-12, in the shallow aquifer and Plattin Limestone. To address the vertical heterogeneity, average uranium concentrations for samples from different depths at the same general location were used to generate the plume maps. The highest uranium activity in groundwater occurs north of the Femme Osage Slough. The vertical and horizontal variation in uranium activity in the alluvial aquifer probably results from lithologic heterogeneities, fracture flow from the quarry, and localized changes in the oxidation potential. These features are schematically illustrated in Figure 9-13.

In the shallow aquifer, uranium activity decreases abruptly near the northern margin of the slough in response to the sudden decrease in the oxidation potential (Figure 9-4) which results in reduction of uranium from the soluble U^{6+} to the insoluble U^{4+} state. The sharp decrease in uranium levels indicates that sorption, which typically generates more diffuse boundaries, plays a minor role in attenuating uranium along this boundary. Sorption is the primary geochemical process along the eastern and western margins of the plume, which show a gradual decrease in uranium levels.

Extensive study has been directed at understanding the geochemical controls on uranium mobility in groundwater, and the results show that in the natural environment, uranium exists in two predominant oxidation states: as uranous in the plus four (U^{+4}) valence state and as uranyl in the plus six (U^{+6}) valence state. Under oxidizing conditions, uranium is in the uranyl form and quite soluble in groundwater (Langmuir, 1978) through the formation of stable complexes. This behavior allows the dissolution and transport of uranium in oxidized environments. Figure 9-4 shows that oxidizing conditions exist in saturated bedrock beneath and south of the quarry proper and in the northern portion of the alluvial aquifer which coincide with the area of elevated uranium activity in groundwater.

Electrochemical reduction of the uranyl ion (U^{+6}) to the uranous form (U^{+4}) leads to the precipitation of uraninite (UO_2) and coffinite (USiO4) and a decrease in the dissolved concentration of uranium in groundwater. The particular precipitating form is dependent on the activity of dissolved silica in the system. The solubility of uraninite (or coffinite) under reducing conditions, which are present in the alluvial aquifer in the vicinity of Femme Osage Slough, is small (Ref. 82). Naturally occurring compounds known to cause the reduction and precipitation of reduced uranium species include hydrogen sulfide (or bisulfide ion), iron disulfide minerals, such as pyrite and marcasite, ferrous iron-bearing species, hydrogen, and organic carbon, many of which have been identified in the alluvial materials north of the slough. For apparently kinetic reasons, methane and ammonia are relatively ineffective at reducing uranyl ion at low temperatures (< 100° C) and are not expected to occur in the quarry area.

Typical uranyl reduction reactions resulting in the formation of uraninite include:

$$4[UO_2(CO_3)_3^{-4}] + HS^- + 15H^+ = 4UO_2 + SO_4^{-2} + 12CO_2(g) + 8H_2O$$

$$UO_2(CO_3)_3^{-4} + 2Fe^{+2} + 3H_2O = UO_2 + 2Fe(OH)_3 + 3CO_2(g)$$

The decrease in the concentration of dissolved uranium upon the precipitation of uraninite (or coffinite) is large, which explains the abrupt decrease in uranium activity in groundwater near the northern margin of Femme Osage Slough. Under oxidizing conditions, uranyl complexes can result in dissolved equilibrium concentrations on the order of hundreds of parts per billion (ppb) or greater. Except for pH conditions below about 2 to 3, the uranous ion concentration is typically less than 0.01 ppb.

Calculations were performed to determine if the uranium contamination in the alluvium north of Femme Osage Slough could have been precipitated or adsorbed from groundwater moving south from the quarry and through the geochemical reduction zone. An area of soil contamination referred to as the Group SQ (Soils south of the quarry and north of the slough) was selected for this analysis because it is in the flow path of the uranium plume migrating in groundwater, and sampling shows that elevated uranium contamination is present in the alluvium. Group SQ is shown on Figure 6-6.

The first calculation was made to quantify the mass of uranium which has moved in groundwater from the quarry and into the alluvium. The following assumptions were made in order to perform the calculation:

- The average concentration of uranium in a cross-section through the plume has been 2829 pCi/L.

- Contaminated groundwater had been flowing into the alluvium from 1970, the approximate time of the first evidence of groundwater contamination, until the present (27 years).

- The volume of flow is approximately 7500 gallons per day or half of the total flow system shown on Figure 8-18.

The calculation to quantify the mass of uranium which has moved in groundwater from the quarry and into the area of contaminated alluvium is as follows:

Groundwater Concentration (Total U) x Time x Flow Quantity = Total Mass

OR

2829 pCi/liter x 27 years x 7500 gal/day = 8×10^{11} pCi

The results of the first calculation show that approximately 0.8×10^{12} pCi of uranium flowed in groundwater from the quarry and into the geochemical reduction zone.

A second calculation was made to quantify the mass of uranium which may have precipitated or adsorbed by the alluvium in the contaminated area north of the slough. The following assumptions were made in order to perform the second calculation:

- The area of contamination is approximately 900 feet by 200 feet and includes borings QRSB-25, QRSB-27, QRSB-35, QRSB-36, QRSB-37, QRSB-38, and QRSB-40.

- The contaminated alluvium is approximately 15 feet thick.

- The weighted average concentration of uranium in the area of contamination is 22.4 pCi/g based on a weighted average of the laboratory results from borings in this area.

The calculation to quantify the mass of uranium which was precipitated or adsorbed by the alluvium in the contaminated area north of the slough is as follows:

Soil Volume x Bulk Density x Soil Concentration (U) = Total Mass

OR

$$900 \text{ ft} \times 200 \text{ ft} \times 15 \text{ ft} \times 100 \text{ lb/ft}^3 \times 22.4 \text{ pCi/g} = 2.7 \times 10^{12} \text{ pCi}$$

The results of the second calculation show that approximately 2.7×10^{12} pCi of uranium were present in the soils prior to remediation of the VP 9 area in 1996. The results of these calculations provide strong evidence that uranium may be removed from groundwater and precipitated or adsorbed by the alluvium in the geochemical reduction zone. Values calculated for groundwater may be lower than that calculated for soils based on historically higher uranium levels being monitored in these wells than the average has accounted for in this calculation. The processes of precipitation and adsorption explain the sharp decrease in the concentration of uranium in the vicinity of Femme Osage Slough shown on the isopleths (Figure 9-12).

South of the slough, slightly elevated uranium levels have been observed in a shallow alluvial monitoring well (MW-1011, mean activity 10.5 pCi/l), temporary piezometers and well point samples (maximum activity 14.6 pCi/l), and in a deeper monitoring well (MW-RMW2 mean concentration 5.67 pCi/l), which is screened over the entire thickness of the alluvium. Plausible sources of this uranium are (1) migration of contaminated groundwater beneath the slough, (2) seepage from the slough, (3) leaching from naturally occurring uranium-rich sediments or from contaminated sediments that were transported and deposited south of the slough during floods, and (4) the Missouri River or other natural sources. None of these sources can be definitively supported or eliminated.

For all locations except MW-RMW2, the first source (migration of contamination beneath the slough) is difficult to support hydrologically because of the downward flow component in the shallow alluvium, as discussed in Section 8. For uranium-contaminated groundwater to travel to these shallow monitoring locations south of the slough, gradients would have to be upward or horizontal. The second source (seepage from the slough) is plausible, but uranium is present at relatively low levels in the slough and may not be soluble in the seepage as it migrates through the reduced zone surrounding the slough. The third source is not supported by soil characterization data; however, soil sampling was not conducted to specifically address this possibility. The fourth source cannot be supported by uranium data from the background locations or from the Missouri River. Although slightly elevated uranium has been detected in the shallow groundwater in the well field, elevated uranium has not been detected in any of the pumping wells, which primarily produce water from the deeper, coarser-grained portions of the aquifer.

Migration of uranium-contaminated groundwater beneath the slough to MW-RMW2, which is screened to bedrock, can be supported hydrologically. Uranium-contaminated groundwater could travel beyond the reduction zone if oxygenated water persists in some areas or if the hydraulic conductivity in preferred pathways such as sand layers is high enough to limit geochemical reactions in the reduced zone.

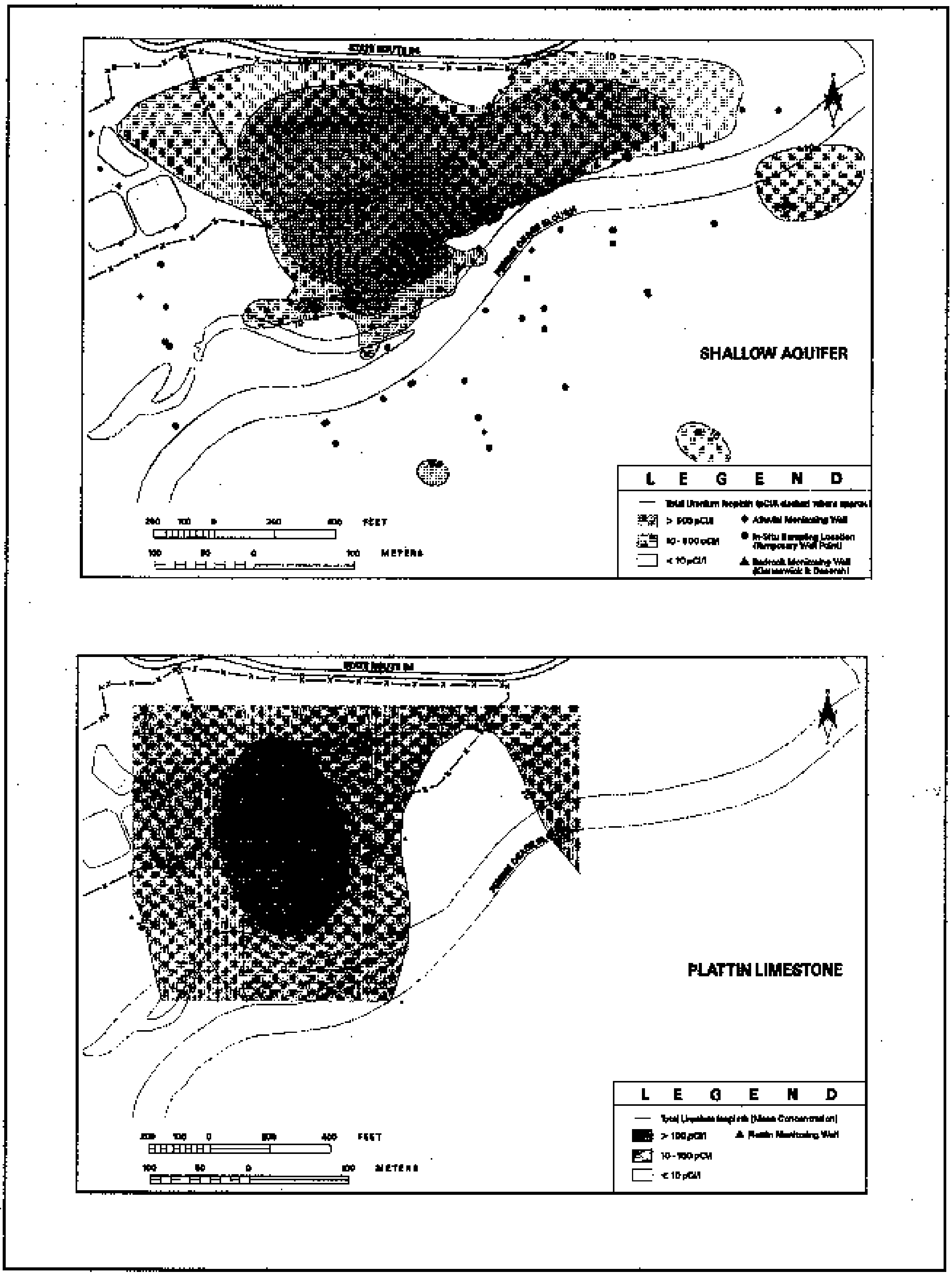
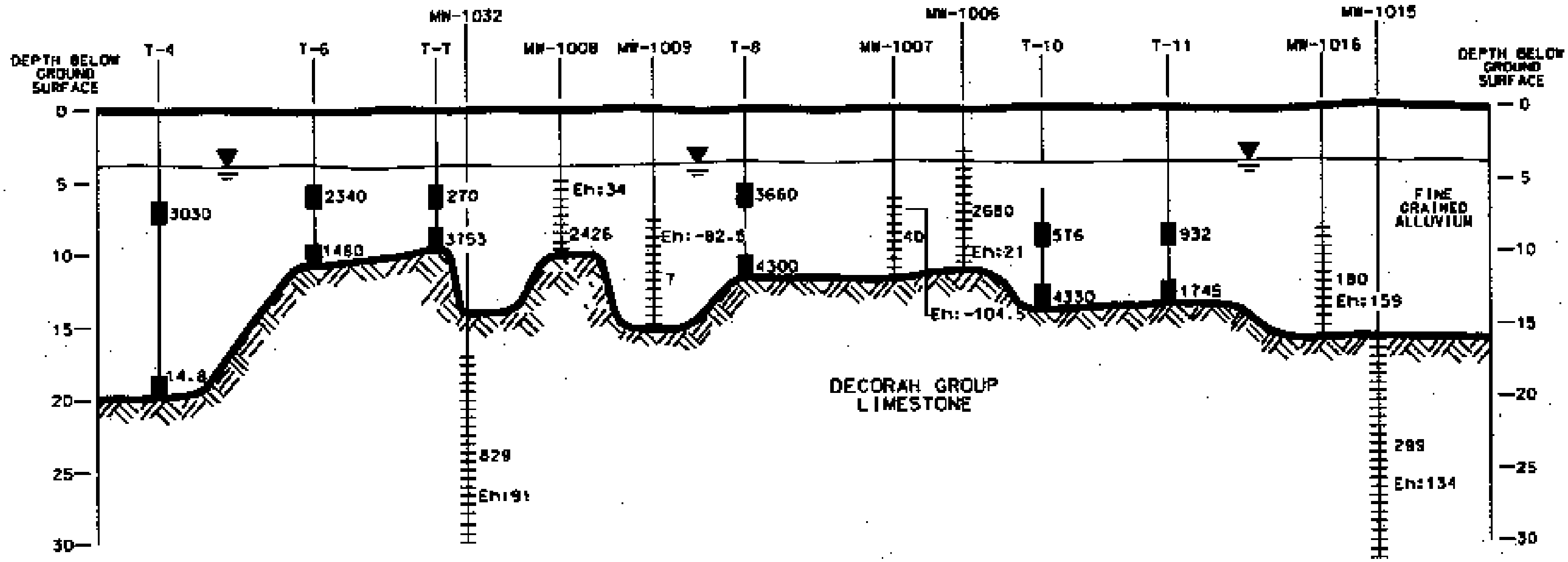


FIGURE 9-12 Groundwater: Uranium Isopleths



LEGEND:

HORIZONTAL SCALE: APPROX 1" = 150' (EXCEPT WHERE WELLS/SAMPLING POINTS REQUIRE SEPARATION FOR PRESENTATION.)
VERTICAL SCALE: 1" = 10' VERTICAL EXAGGERATION APPROXIMATELY 15 TO 1.

= APPROXIMATE SHALLOW GROUNDWATER SURFACE.

270 = IN-SITU SAMPLE INTERVAL (18") SHOWING TOTAL URANIUM CONCENTRATION IN pCi/l.

2436 = MONITORING INTERVAL SHOWING MEAN TOTAL URANIUM CONCENTRATION IN pCi/l.

Eh: = OXIDATION POTENTIAL IN mV.

FIGURE 9-13 SCHEMATIC SECTION SHOWING URANIUM VARIABILITY IN GROUNDWATER

Accelerated transport of uranium-contaminated groundwater along layers of sand or gravels that extend beneath the slough (see Section 8) is a plausible explanation for the elevated uranium levels at MW-RMW2. In addition to limiting reaction time, such zones are unlikely environments for accumulation of decaying organic matter. Although these scenarios are reasonable, an obvious pathway connecting MW-RMW2 to the uranium plume north of the slough could not be identified, and therefore is not shown in Figure 9-12. If uranium observed in MW-RMW2 is related to the plume emanating from the quarry, the fractional contribution from this source to groundwater near this well appears to be relatively constant. As shown in Figure 9-14, uranium levels in MW-RMW2 have varied randomly about a mean value of approximately 5.6 pCi/l for the past 10 years. This random distribution and the absence of trends in the data indicate that steady-state conditions have probably been established at MW-RMW2. Although uranium derived from locations north of the slough may be reaching MW-RMW2, it has not been detected at above-background levels in the pumping wells that supply water to St. Charles County.

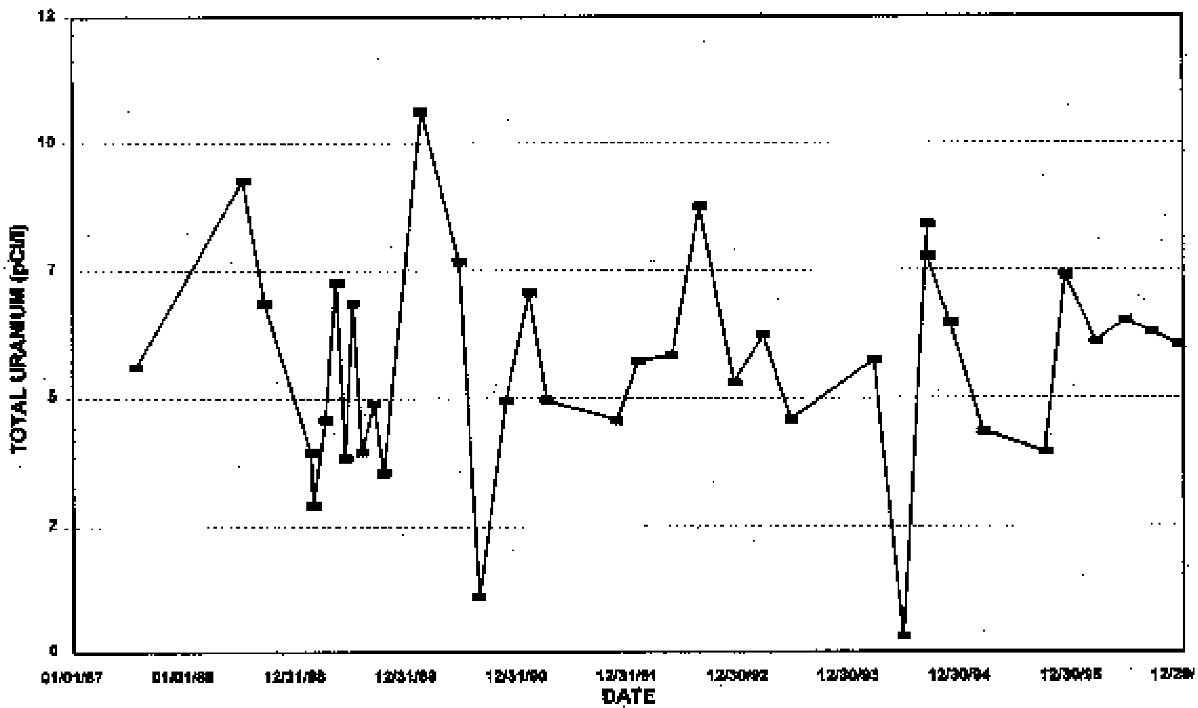


FIGURE 9-14 Historic Uranium Levels at MW-RMW2

Uranium levels and impacted locations have not been strongly influenced by quarry remediation activities. Although levels were generally higher during the remediation period and lower at the end of the period, these trends are not readily apparent. To illustrate this point, historic uranium data from representative alluvial and bedrock wells are shown in Figure 9-15.

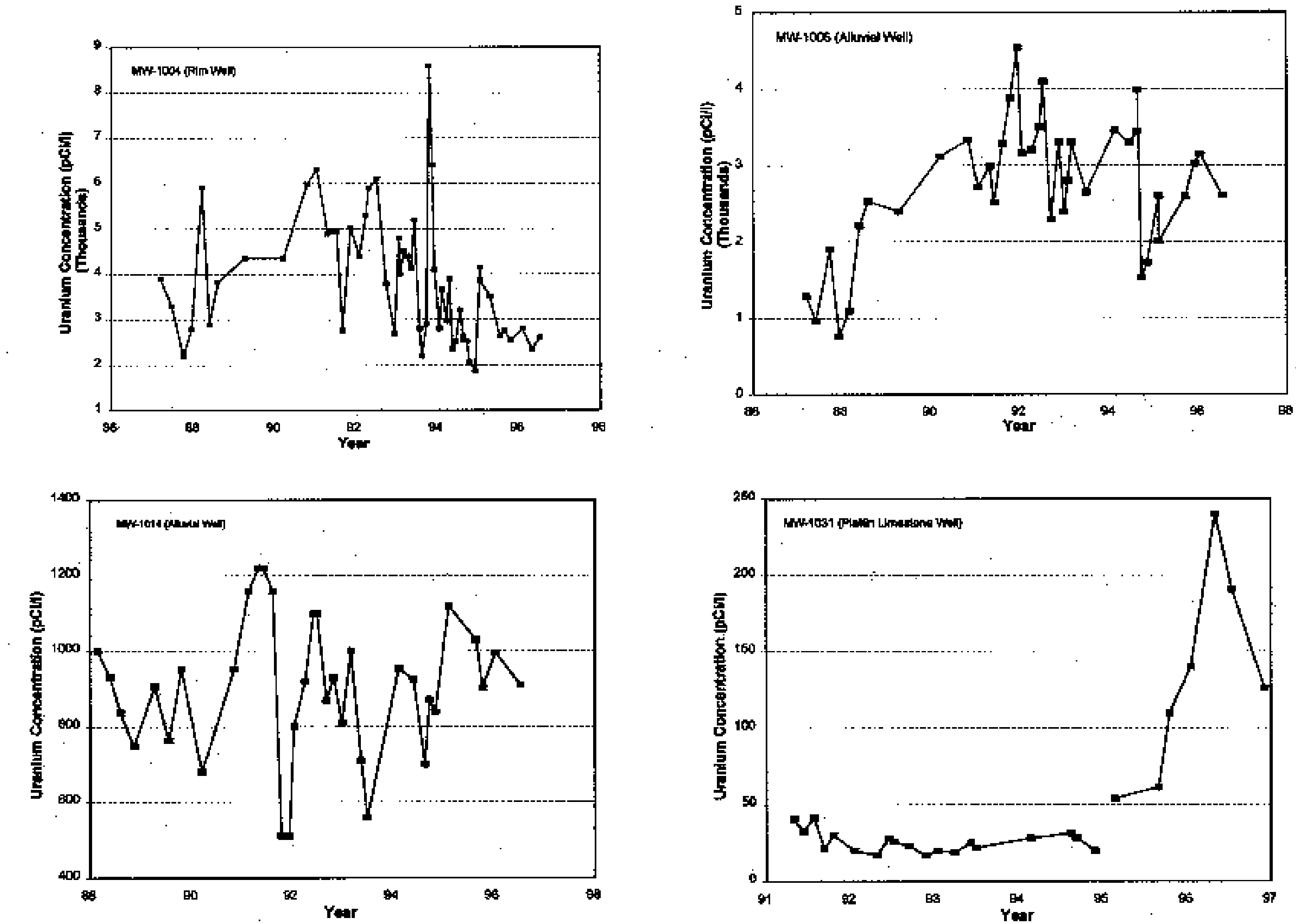


FIGURE 9-15 Historic Uranium Levels at Selected Monitoring Wells

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The most striking aspect of these figures is the short-range variability. This variation appears to be unrelated to seasonal effects because trend analyses performed for annual site environmental reports (Refs. 40, 41, 42) have not shown periodicity in the historic data. In addition, historic patterns from neighboring wells show no correlation. Some variation may be related to flood-induced changes in the aquifer and to quarry activities, but additional processes, such as groundwater mixing in the aquifer or in the well during sampling, are probably involved.

In contrast to the shallow aquifer, uranium activity at one location in the shallow Plattin Limestone increased after conclusion of bulk waste removal, as shown by historic trend at MW-1031 (Figure 9-15). By late 1996, however, the activity began to decrease. The trend observed at this well probably reflects a delayed response to waste removal activity in the quarry due to the extremely low conductivity of the Plattin Limestone.

9.5.4 Arsenic

Arsenic is present at significantly elevated levels in the alluvial groundwater along the southern margin of the Femme Osage Slough (Figure 9-16). As shown in Figure 9-17, high arsenic levels typically are associated with elevated levels of dissolved iron, low levels of sulfate, and low Eh measurements. As described in Section 9.3.3, this assemblage (i.e., high iron, high arsenic, low sulfate, and low Eh levels) is indicative of a strongly reducing environment. This conclusion is also supported by field observations. Field personnel noted the odor of H_2S (sulfide gas) in soil borings collected from these areas. Elevated arsenic levels are not present in the oxidized portions of the fine-grained alluvial aquifer, the deep coarse-grained portion of the alluvial aquifer, or in bedrock groundwater.

The waste stored in the quarry is an unlikely source for elevated arsenic measured in groundwater south of the slough. Although characterization of the quarry wastes identified arsenic as a contaminant (Ref. 4), elevated arsenic levels were not detected in the quarry pond (Refs. 37, 38, and 39), which was in direct contact with the waste. Further indication that arsenic was not readily leached from the wastes was provided by results from Toxicity Characteristic Leaching Procedure (TCLP) tests performed on the wastes removed from the quarry. TCLP tests are designed to simulate leaching from a landfill into the groundwater system under slightly acidic conditions. These conditions are similar to those that existed in the quarry as slightly acidic precipitation fell on the wastes. Results from the TCLP tests (Appendix H, Table H-9) showed that all samples were below the TCLP limit, and most were below the level of detection, indicating that arsenic was not readily leached from the bulk wastes.

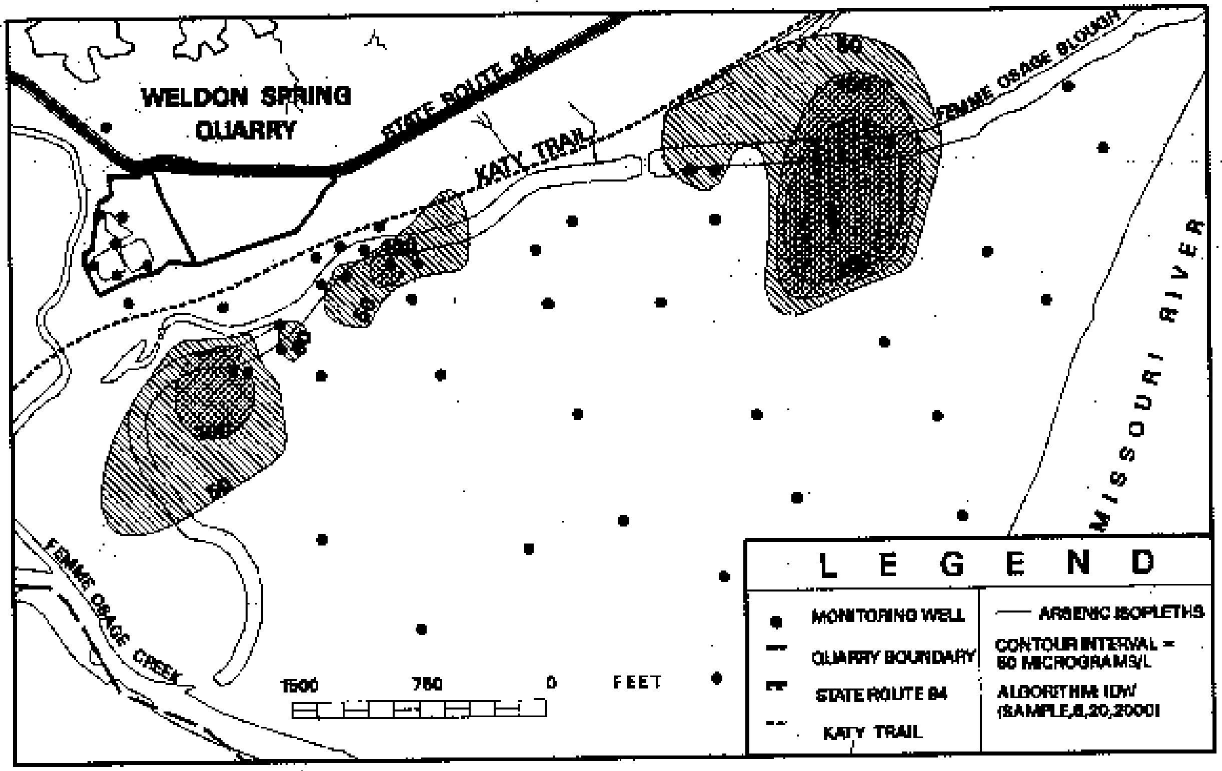


FIGURE 9-16 Groundwater: Arsenic Isopleths for the Shallow Aquifer

High arsenic levels have not been detected in groundwater samples from wells located north of the slough. However, arsenic could have been transported across this area undetected in colloidal iron-manganese oxides that were removed when groundwater samples were filtered. To evaluate the quarry as a potential arsenic source, data from filtered samples were compared with data from unfiltered samples, which would have yielded elevated levels if arsenic was present in colloidal phases. The similar, low levels of arsenic measured in the filtered and unfiltered samples (Appendix H) indicate that colloidal transport is unlikely.

A study of naturally occurring arsenic in groundwater (Ref. 63) has shown that elevated arsenic levels are common where reducing conditions and low hydraulic conductivities exist in floodplains of midwestern rivers. The authors of this study concluded that the most plausible source for this arsenic is reduction and dissolution of iron-manganese oxides, which absorb arsenic from river or stream water. These oxides typically occur as colloidal phases that are carried in suspension by the rivers and are deposited with fine-grained alluvium in low energy areas of the floodplain. Typically these areas also accumulate decaying organic matter, which creates the reducing conditions that eventually dissolve the oxides and release arsenic to the groundwater. This description is consistent with the characteristics of the area adjacent to the slough where high arsenic levels are found.

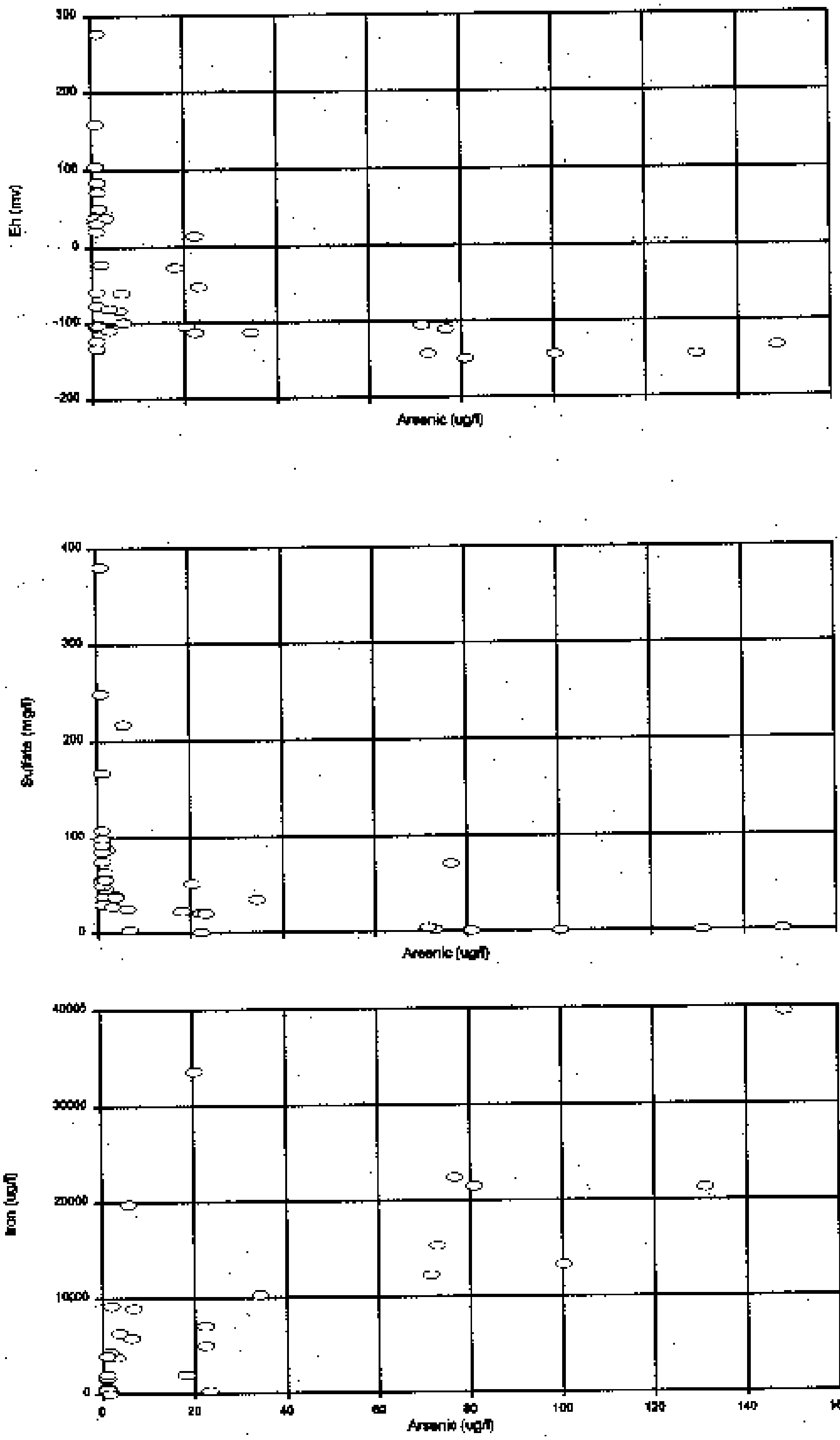


FIGURE 9-17 Groundwater: Relationship Between Arsenic and Redox Sensitive Parameters

9.5.5 Miscellaneous Metals

Aluminum was present at elevated levels at several locations. Although aluminum may have been present in the quarry wastes, it was not a major constituent and it is not soluble in the pH-Eh range that has existed in the quarry aquifers. The likely source of aluminum is inclusion of naturally occurring sediments and colloidal clay particles in groundwater samples.

Iron and manganese behave similarly to aluminum under oxidizing conditions but become soluble as the oxidation state decreases. Both elements occur naturally in aquifer minerals, which are considered to be the primary source for these groundwater contaminants.

Thallium levels are above the threshold that defines a contaminant (Section 3) and slightly exceed the MCLs. Because detection limits for thallium are often higher than the water quality standard (2 μg/L), it is difficult to determine whether the calculated $UCL95_s$ values reflect groundwater contamination or are artifacts of the lack of sensitivity in the analytical technique.

Thallium was found at low levels in the bulk wastes, and slightly elevated thallium values have been detected in other media sampled for this investigation. The thallium occurrences have been sporadic, however, and are difficult to attribute to a single source. Additional sampling will be performed with detection limits less than the MCL to verify its presence in groundwater.

Antimony levels exceed the MCL. Because detection limits for antimony are significantly higher than the water quality standard (6 μg/l), it is difficult to determine whether the calculated UCL95 values reflect actual concentrations or are artifacts of the lack of sensitivity of the analytical method. Additional sampling will be performed with a detection limit less than the MCL to verify its presence in groundwater.

9.6 Significant Observations

- Uranium and nitroaromatic compounds are the primary quarry-derived contaminants in groundwater.

- Contaminant plumes are limited to the north side of the slough. Low levels of uranium have been measured at two monitoring wells south of the slough: RMW2 (average value = 5.67 pCi/l) and 1011 (average value = 10.5 pCi/l).

- The rapid decrease in groundwater contaminant levels at the slough probably results from a reducing zone that degrades nitroaromatic compounds and precipitates uranium-bearing phases.

- Elevated arsenic levels along the slough are most likely unrelated to quarry wastes.

- Concentrations of nitroaromatic compounds are decreasing in response to bulk waste removal and are expected to continue decreasing, whereas uranium concentrations have shown little decline. The persistence of uranium indicates secondary sources are present, namely alluvial soils and aquifer materials, located north of the slough.

- Antimony and thallium values may exceed the MCLs but, due to the high detection limits, the existing data cannot be used for comparison. Additional samples will be obtained and analyzed using detection limits less than or equal to the MCL for evaluation.

10 CONTAMINANT FATE AND TRANSPORT

In this section, significant observations concerning the nature and extent of contamination in all media are integrated to form a conceptual model showing the distribution and movement of contaminants in the quarry environmental system. The major processes and observations that form the basis for this model are described elsewhere in this report. In this section, they are briefly summarized in tables. Near the end of this section, the conceptual model is presented in graphical form, and projected future conditions in the quarry system are examined with respect to the conceptual model.

10.1 Residual Contaminated Media

Contaminants were first introduced into the environment when wastes were placed in the quarry and wastewater was discharged from the Weldon Spring Ordnance Works into the Little Femme Osage Creek. Although bulk waste has been removed from the quarry and only low levels of contamination are present in runoff from the former ordnance works, some contamination persists in various media: soils, surface water, sediments, and groundwater. In the vicinity of the quarry, some of these media contain high concentrations of one or more quarry-related contaminants. Significantly contaminated media (i.e., media with levels of contamination greater than two times background or greater than the water quality or screening guideline levels presented in Section 3) are summarized in Table 10-1.

TABLE 10-1 Summary of Contaminated Media in the Quarry System

MEDIUM	LOCATION	CONTAMINANTS	
		Major[a]	Minor[b]
Soil	Quarry Proper	Ra-226, Ra-228, Th-230	Metals, U, Nitroaromatic Compounds, PAHs, PCBs
	North of Slough	None	Metals, F, U
Sediment	Slough	None	U, Metals,
	Little Femme Osage Creek	None	U, Metals
Surface Water	Slough	U	Metals, Anions,
	Little Femme Osage Creek	None	Nitroaromatic Compounds
Groundwater	Alluvium, North of Slough	U, Nitroaromatic Compounds, Tl	SO_4
	Decorah Group, North of Slough	U, Nitroaromatic Compounds	SO_4
	Plattin Limestone, North of Slough	U	None
	Alluvium, South of Slough	None	U

(a) Major contaminants: > water quality standards or 10-5 risk level
(b) Minor contaminants: > 2 x background and < water quality standard or risk 10-5 level

10.2 Transport Mechanisms

Before a quarry-related contaminant can occur in media outside the quarry, a transport mechanism or agent must be available. The characteristics of available transport mechanisms in the vicinity of the quarry are summarized in Table 10-2. As the table indicates, the primary transport agent is water, mainly groundwater. Although some contaminants were transported by wind prior to bulk waste removal, this pathway is now insignificant.

TABLE 10-2 Potential Mechanisms Affecting Contaminant Transport

TYPE	AGENT	MATERIAL TRANSPORTED	CONTAMINANTS	SIGNIFICANCE
Physical Transport	Air (wind)	Fine-grained loose surface soil or waste material	Any contaminant physically/chemically attached to solid	Insignificant since removal of waste
	Surface Water, quarry proper	Soils and small particles of other solids and dissolved contaminants	Any contaminant physically/chemically attached to solid	Limited to surface runoff collected in quarry
	Surface Water, outside quarry proper	Soils and small particles of other solids and dissolved contaminants	Any contaminant physically/chemically attached to solid	Minor except for Missouri River during flood stage
	Groundwater	Extremely fine solids and colloidal material	Any contaminant physically/chemically attached to solid	Potentially significant in bedrock fractures
Solute Transport	Surface Water	Dissolved and complexed anions and cations	U, SO_4, nitroaromatic compounds	Significant in surface water inside and outside the quarry
	Groundwater	Dissolved and complexed anions and cations	U, SO_4, nitroaromatic compounds	Significant in both alluvium and bedrock
Diffusion	Air	Gas exsolved from radium-contaminated soil	Radon	Insignificant since removal of waste

10.3 Geochemical Behavior of Contaminants

During transport in water, contaminants may be attenuated by several processes which are summarized in Table 10-3. Some of these processes are reversible, i.e., if conditions change, the contaminant could be released back to the transporting medium. Dissolution-precipitation and sorption-desorption reactions are the major geochemical processes that control the mobility of major quarry-related contaminants in water. These processes, which are described in Section 9, control the mobility of contaminants in groundwater as well as surface water.

Table 10-3 shows the environmental conditions that affect the solubility of major quarry-related contaminants and the sorption capacity of affected media for these contaminants. With the exception of Eh, system parameters that can affect contaminant solubility or sorption (i.e., temperature, pressure, and pH) vary slightly in the quarry environment. Because these parameters are essentially invariant, they are not discussed here.

TABLE 10-3 Geochemical Behavior of Quarry-Related Contaminants in Water

CONTAMINANT /SOLUBLE FORM	SOLUBILITY		RELATIVE SORPTION CAPACITY		
	OXIDIZING CONDITIONS[a]	REDUCING CONDITIONS[b]	SOIL[c]	ORGANIC MATERIAL[d]	BEDROCK[e]
Uranium Soluble as anionic complex	**Soluble**; for U^{6+} valence, mobility enhanced by formation of anionic complexes with carbonate ion	**Very low solubility**; for U^{4+} valence, concentration levels limited by precipitation of uranium oxides and silicates	**Fair**, limited by content of Fe-Mn oxides and organic matter	**Good**	**Poor**
Nitroaromatic Compounds	**Moderately soluble**	**Moderately soluble**	**Poor** on silicate minerals (clays, quartz, etc)	**Good**, organic material also favors degradation through microbial processes	**Poor**
Sulfate Soluble as anionic complex	**Good**; for S^{6+} valence, concentration levels limited by precipitation of barite ($BaSO_4$) and anhydrite ($CaSO_4.H_2O$)	**Poor**; for S^{2-} valence, concentration levels limited by precipitation of sulfide minerals	**Poor**, limited by anion sites and by competition with more strongly sorbed anions	**Limited** by competition with more strongly sorbed anions	**Poor**
Radium Soluble as cation	**Poor**; concentration levels limited by formation of radium sulfates and other minerals	**Not affected by changes in Eh**	**Good**	**Good**	**Poor**
Thorium Soluble as cation	**Poor**; concentration levels limited by formation of thorium oxides and hydroxides	**Not affected by changes in Eh**	**Good**	**Good**	**Poor**

(a) Oxidizing conditions result from exposure to the atmosphere, infiltration of oxidized water, and the presence of oxidized phases in the aquifer.
(b) Reducing conditions result from the presence of decaying organic matter and the presence of reduced phases in the aquifer.
(c) Anion sorption is minor, controlled by organic content of soil, and limited to Fe-Mn oxides.
(d) Large surface area, excellent sorption of cations and good sorption of anions.
(e) Small surface area limits cation sorption; anion sites typically insignificant.

10.4 Potential Contaminant Sources

Contaminant sources that persist in the quarry environmental system are listed in Table 10-4, and are based on information summarized in the previous tables. The significance of these sources is related to risks that may result from release and migration of contaminants from these sources to biological or human receptors. These issues are evaluated in the *Baseline Risk Assessment*, which accompanies this document.

TABLE 10-4 Remaining Sources of Mobile Contaminants

SOURCE	LOCATION	MOBILE CONTAMINANT	TRANSPORT AGENT	IMPACTED MEDIA
Soil	Quarry fractures	Uranium	Surface water/ groundwater	Groundwater; surface water (quarry pond)
	Alluvium north of slough	Uranium	Surface water/ groundwater	Groundwater; soil; surface water (slough)
Groundwater	Quarry fractures; alluvial and bedrock aquifers north of slough	Uranium; nitroaromatic compounds; sulfate	Surface water/ groundwater	Groundwater; soil; surface water (slough)
Surface Water	Femme Osage Slough	Uranium	Surface water/ groundwater	Groundwater; sediment; surface soil
	Little Femme Osage Creek	Nitroaromatic compounds	Surface water	Sediment
	Quarry pond[a]	Uranium	Groundwater	Groundwater/soil
Sediment	Femme Osage Slough	Uranium	Surface water/ groundwater	Surface water; groundwater

(a) Minor source because concentrations are significantly lower than those in groundwater downgradient from pond.

10.5 Conceptual Model

Figure 10-1 represents the conceptual model of the quarry system. The model includes historic sources (now removed) and currently active sources, which may continue to disperse contamination. The model describes the fate of each contaminant and shows how each is transported. It also identifies processes that occur as water moves from the quarry toward the St. Charles County well field.

These processes contribute to the reduction of contaminant concentrations, which are relatively high north of the Femme Osage Slough, to near background levels south of the slough. These are redox reactions, dilution, and sorption.

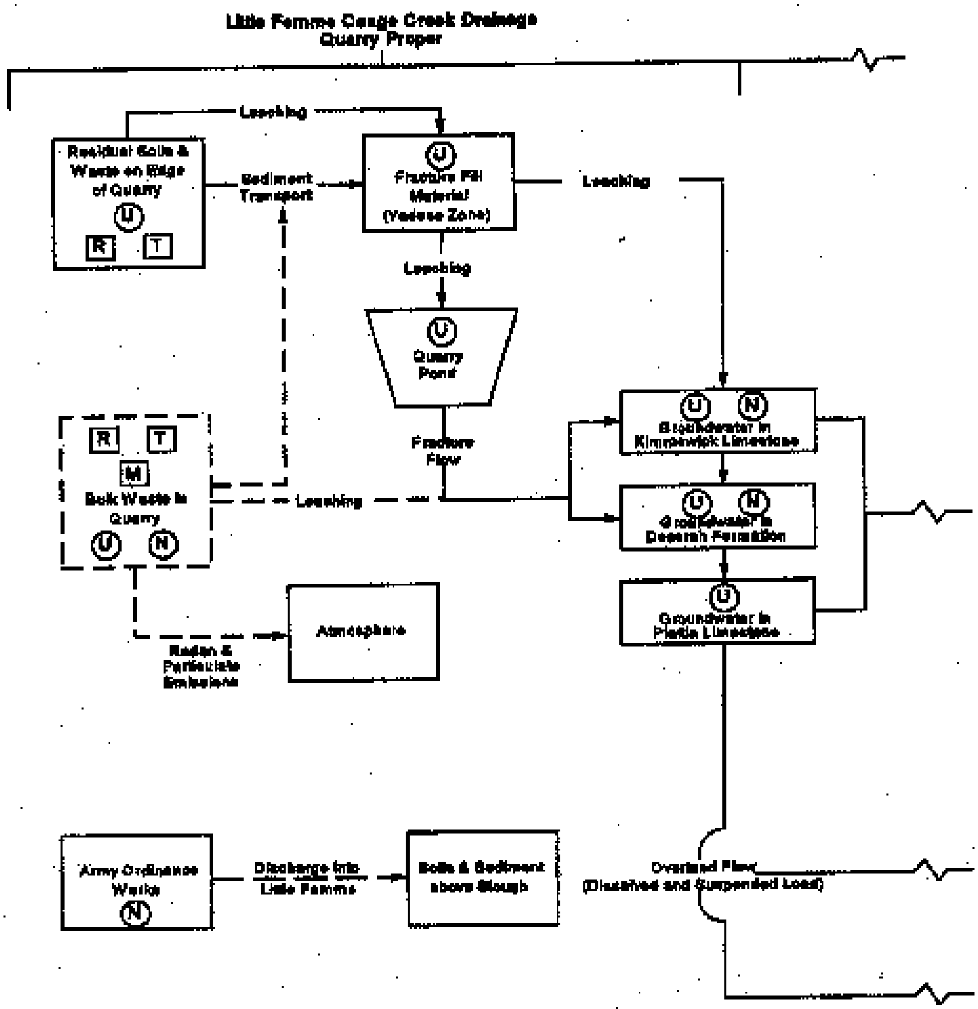
10.5.1 Redox Reactions

Redox reactions are a significant cause of the sharp decrease in uranium, sulfate, and nitroaromatic compound concentrations that occurs near the northern margin of the Femme Osage Slough. As described in Section 9, these reactions reduce uranium and sulfur to lower oxidation states at which they form insoluble compounds. The primary nitroaromatic compounds also degrade in response to lower oxidation potentials and microbial activity that occurs in this area.

The strongly reducing environment associated with the Femme Osage Slough is schematically shown in Figure 10-2. This area, which is primarily composed of fine-grained sediments and clays, is expected to be coincident with the permanently saturated zone beneath the slough. Seepage from the slough, which maintains saturated conditions in the soil, is probably responsible for the persistence of low oxidation potentials in this zone. In addition to physically preventing diffusion of oxygen into this area, this seepage is also a source of highly reduced soluble species derived from decay of organic material at the base of the slough.

The reduced zone extends downward (probably to bedrock in most locations) and outward from the slough. It extends south of the slough due to the prevailing hydraulic gradient and interaction with oxygenated groundwater along the northern slough margin. The variability in redox sensitive parameters in some monitoring wells located directly north of the slough suggests that the northern margin is characterized by interfingering of reduced and oxidized sediments and that it probably shifts back and forth in response to seasonal variation in slough and groundwater levels. This shift is exhibited in wells MW-1007 and MW-1009, which are located within 50 feet from the edge of the slough.

The fine-grained silts and clays found in most soil borings from areas immediately adjacent to the slough and the sharp change in groundwater contaminant concentrations on opposite sides of the slough indicate that the reducing zone is a continuous feature that intercepts most alluvial groundwater traveling south from the quarry area toward the well field. This redox barrier is probably penetrated in a few areas by stringers of sand, which may occur at any depth but are most likely to be present in bedrock depressions associated with paleodrainages. If reaction kinetics are sufficiently slow, the higher permeabilities in these stringers could allow contaminants to persist in their soluble, oxidized state and thus migrate toward the well field. This possibility is indicated by the dashed lines crossing the reduction zone in Figure 10-1. These permeable areas are not abundant, however. With one exception, groundwater samples from deep alluvial well points and monitoring wells south of the slough have yielded background levels of uranium. As



(1) Groundwater discharge into localized areas of Femme Osage Slough.

(2) Includes possible desorption of contaminants in unsaturated alluvium during high water periods.

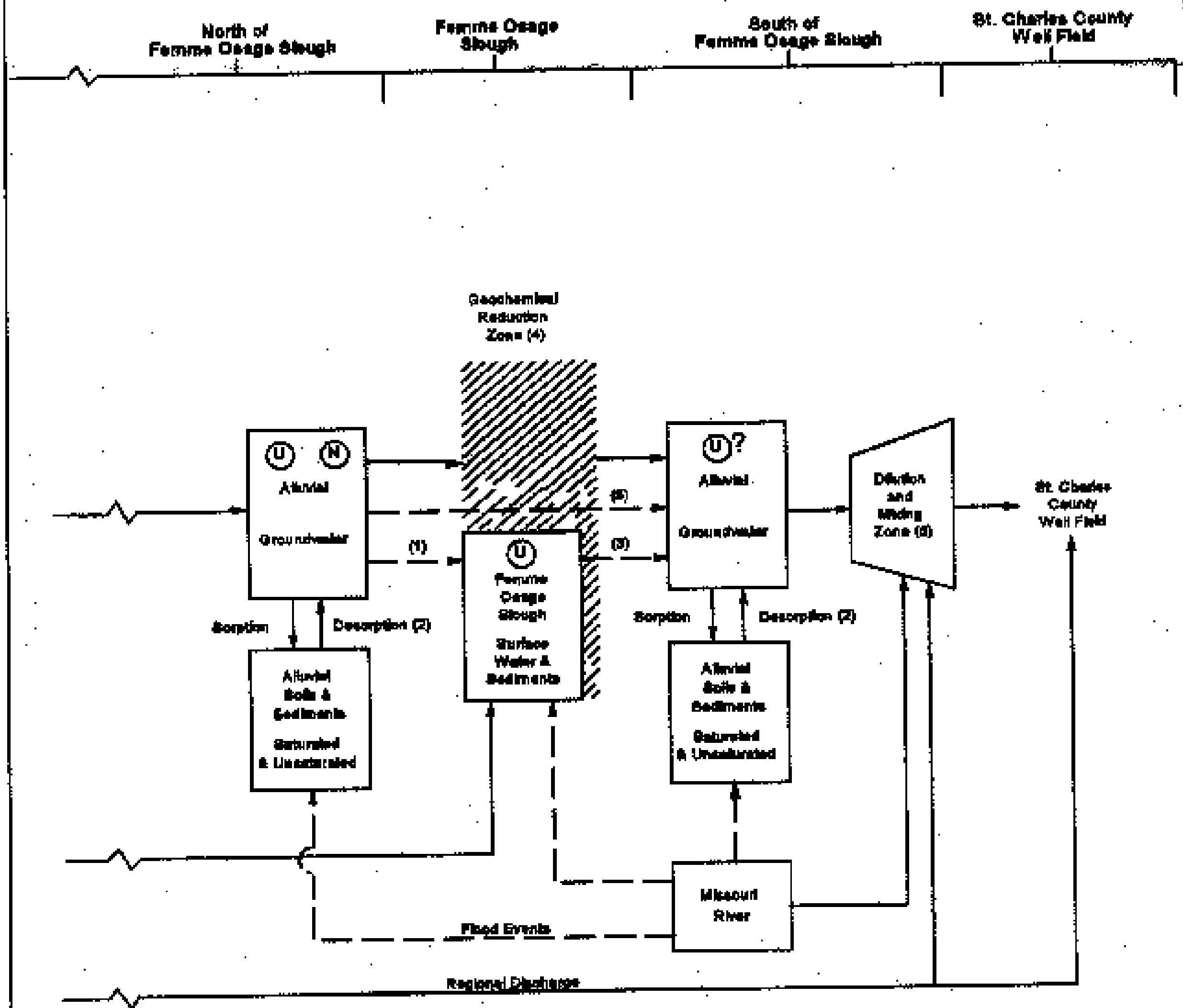
(3) Leakage from slough into alluvium.

(4) Degradation of nitroaromatics; precipitation of uranium and sulfide phases.

(5) Possible incomplete precipitation of contaminants along preferential flow pathways in coarse basal alluvium.

(6) Includes alluvium southeast of Femme Osage Slough and northwest of the St. Charles County Well Field.

FIGURE 10-1 Conceptual Fate and Transport Model for the Quarry Area



Notes: Precipitation is a principal agent in all fate & transport process and is an important factor in the dilution and mixing zone.

Dashed lines indicate localized, intermittent, or seasonal events.

Dotted lines indicate the source/pathway was eliminated in 1995 with bulk waste removal.

(U) = Uranium
(N) = Nitroaromatic Compounds
} Indicate sources of mobile contaminants to the hydrologic system.

R = Radium
T = Thorium
M = Metals
} Indicate location of immobile contaminants.

FIGURE 10-1, Continued

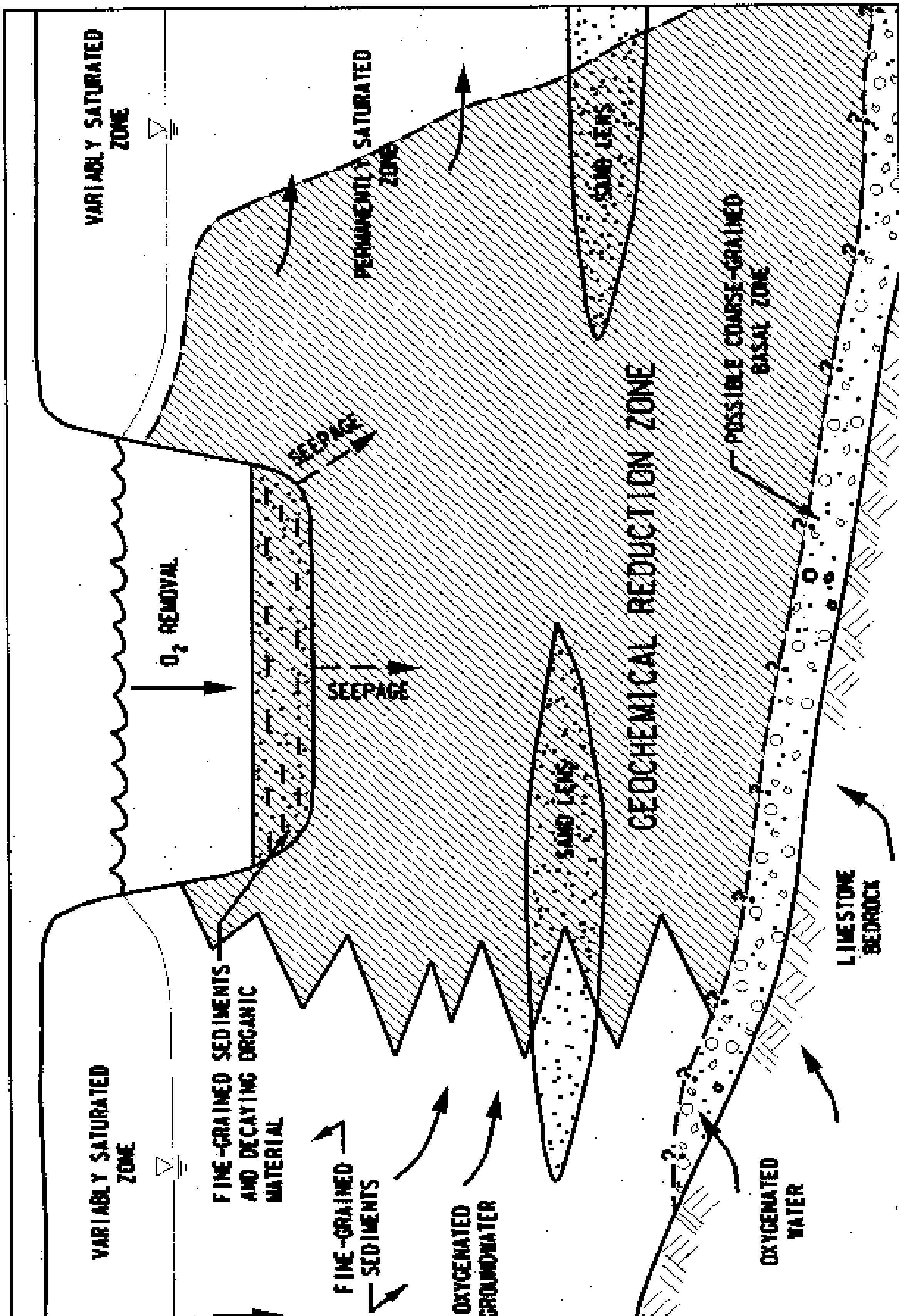


FIGURE 10-2 Schematic Diagram of Reduction Zone in the Vicinity of Femme Osage Slough

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discussed in Section 9, the exception is MW-RMW2, which has displayed a stable range of uranium concentrations for the past 10 years.

Because of the reduced nature of the soils, uranium should not be soluble in water seeping from the slough, with the possible exception of water migrating within a few millimeters of the air-water interface. Thus, elevated uranium levels observed in groundwater at shallow alluvial locations south of the slough are unlikely to be related to the slough.

10.5.2 Dilution

Dilution and mixing become progressively greater as groundwater migrates toward the St. Charles County well field. As discussed in Section 8, groundwater originating from areas north of the slough is a small fraction of the total water budget for the well field. Induced infiltration from the Missouri River is the primary source of water.

10.5.3 Sorption

Sorption onto saturated and unsaturated soils and sediments has limited groundwater and surface water transport of many radionuclides, metals, and organic compounds. Based on the observed contaminant distributions to redox reactions, however, sorption is less significant than redox reactions for attenuating uranium. Sorption continues to occur on the western and eastern margins of the plume, slowing lateral migration of uranium-contaminated groundwater.

10.6 Simulation of Potential Migration of Contamination to the St. Charles County Wellfield

The St. Charles County wellfield is located in the area between the slough and the Missouri River. Eight production wells are used on a rotating basis to pump an average of 10.5 mgd from the coarse-grained materials of the Missouri River alluvium. Uranium contamination has been identified in a few monitoring wells and piezometers south of the slough and there is concern that the operation of the production wells will eventually draw contaminated water or existing natural processes will not adequately limit the migration of uranium into the area where the production wells are located.

A model was completed to estimate migration pathways of uranium contaminated groundwater originating from north of the slough, the contaminant distribution within the plume, and the concentration of the discharge from the wells capturing the plume for a 20-year simulation period (Appendix I). It is expected that a large amount of dilution takes place at the wells because the primary source of the water to these wells is derived from the Missouri River. The model provides an estimate of the uranium concentration that could occur in the wellfield under the hypothetical scenario of a complete breakthrough of contamination past the reducing environment adjacent to the slough. A complete description of the model is provided in Appendix I.

The following assumptions form the basis for the model scenarios presented in this remedial investigation:

- All chemical or hydraulic barriers to migration of the uranium plume toward the wellfield do not exist.
- Average, steady-state hydrologic conditions exist
- Chemical transport will be based on the simulated steady-state hydrologic conditions.
- The source of uranium contamination to the wellfield area is uniform and continuous and originated from the area north of the slough.
- The average concentration of the plume along a cross section perpendicular to the flow is 2829 pCi/l.

The modeled area is bounded by the Katy Trail, the Missouri River, and an arbitrary boundary a few miles southwest of the Femme Osage Creek. This simulation assumes there is no seepage from the slough or the Femme Osage Creek.

10.6.1 No Pumping Scenario

A steady-state condition with no pumping of the production wells was run to simulate a migration pathway for the uranium plume should operation of the wellfield stop (Figure 10-3). In general, groundwater levels are maintained at approximately the same levels as the water level in the Missouri River. The direction of groundwater flow is almost parallel to the Missouri River. The path taken by the contaminant plume is parallel to the bedrock/alluvium contact and eventually discharges to the Missouri River.

10.6.2 Wellfield Pumping Scenario

Steady-state hydrologic conditions with operation of the production wells were simulated to determine the migration pathway for the uranium plume (Figure 10-4). A base transport condition with no dispersion or retardation was simulated to illustrate the impact of dilution from the production of the wells on contaminant migration (Figure 10-5). Two contaminant transport conditions were simulated to illustrate the impact of dispersion and retardation on the movement of the contamination (Figures 10-6 and 10-7). Dispersion is a mechanical process that has the affect of spreading the plume along the flow path and reducing the levels the concentration. Dispersion perpendicular to the flow path (transverse) is generally less than the dispersion in the direction of flow (longitudinal). Dispersion increases the velocity of the contaminant movement in both the transverse and longitudinal direction so that a plume with dispersion will arrive at a point in the flow path before a plume without dispersion. Retardation is a function of limited adsorption of contaminant on the aquifer matrix and reduces the velocity of the contaminant movement.

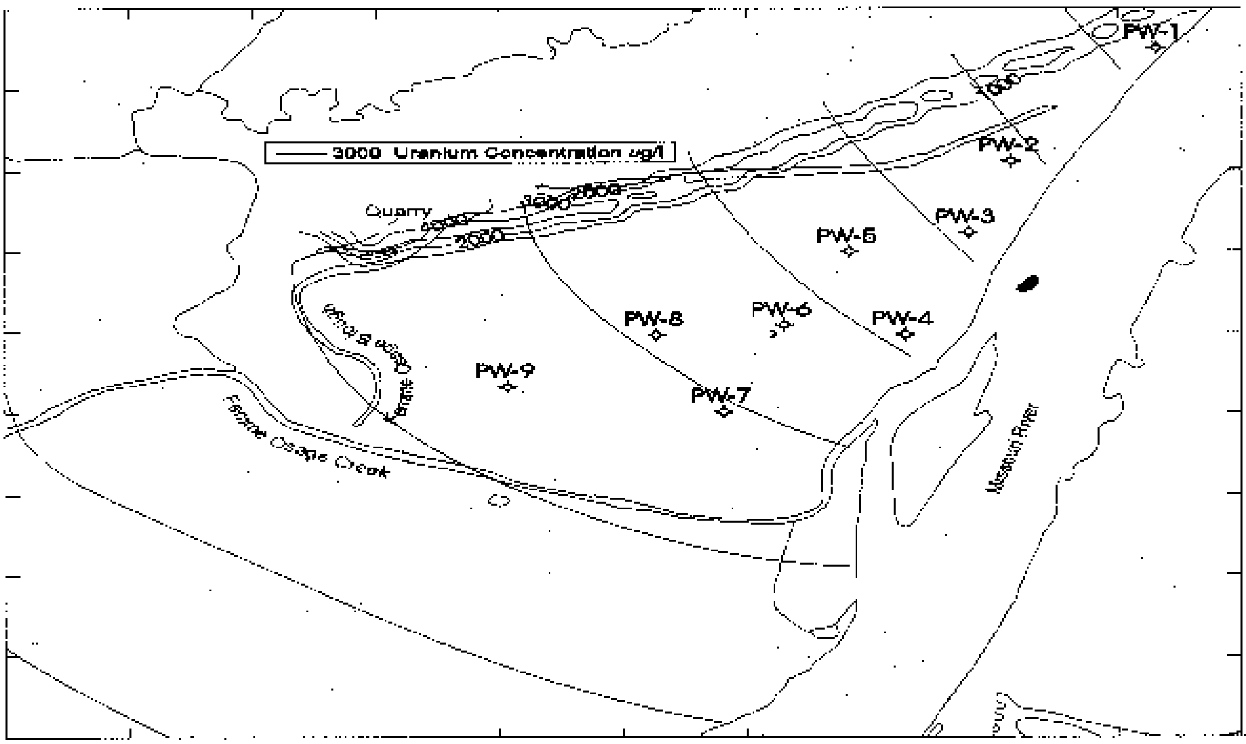

FIGURE 10-3 Uranium Isopleths for the Simulated Quarry Plume without Groundwater Pumping

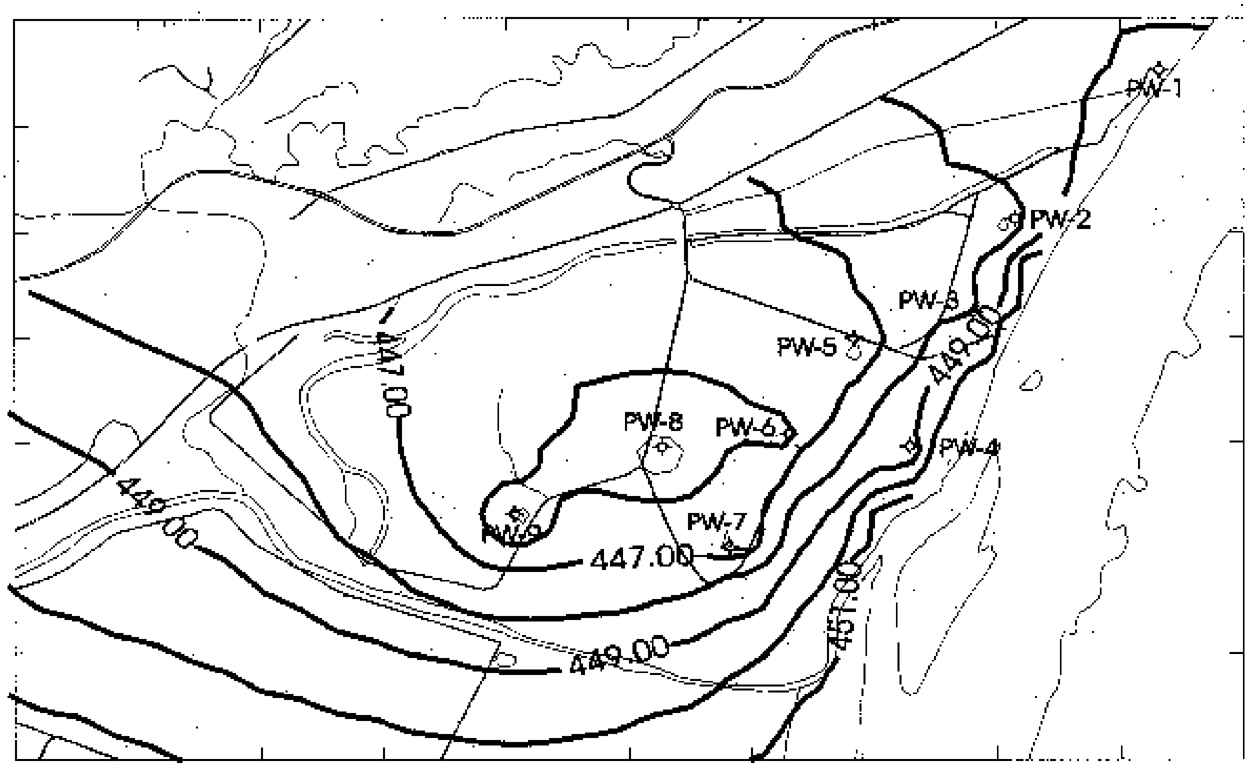

FIGURE 10-4 Simulated Steady-State Groundwater Level Contours

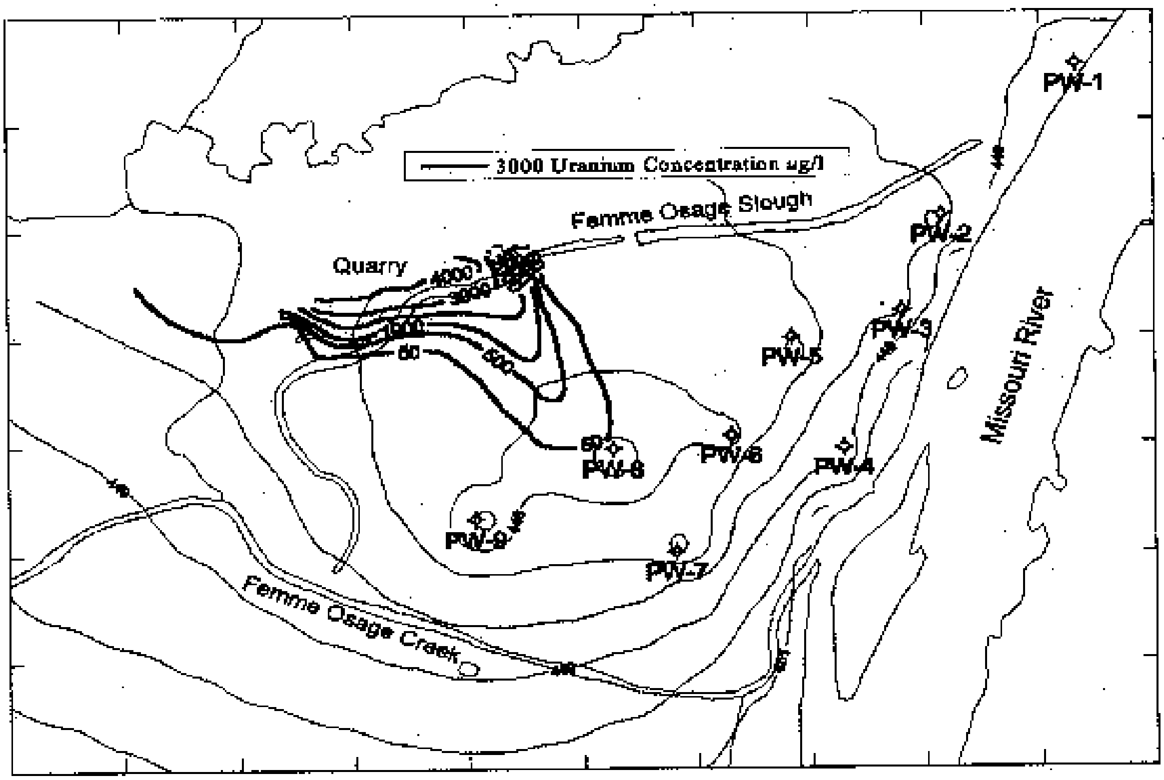

FIGURE 10-5 Uranium Isopleths for the Simulated Quarry Plume without Dispersion or Retardation

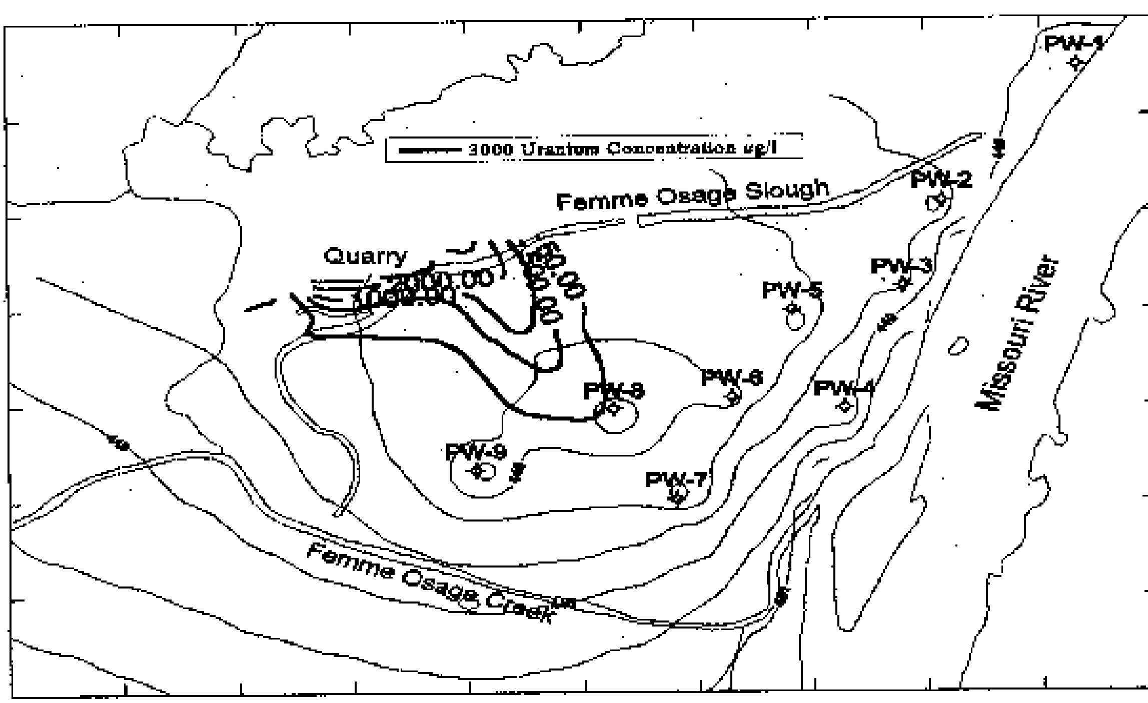

FIGURE 10-6 Uranium Isopleths for the Simulated Quarry Plume with Dispersion

Simulation with no dispersion or retardation indicates that after 20 years the contaminant plume is primarily captured by PW-8 (Figure 10-5). Under these conditions, minor impacts are observed in neighboring PW-9. The uranium level in groundwater produced from PW-8 and PW-9 are 5 μg/l (3.4 pCi/l) and 0.15 μg/l (0.1 pCi/l), respectively.

The configuration of the plume with dispersion (Figure 10-6) at 20 years shows very little apparent difference in the contours. A value of 20 ft was used for dispersion. There is a significant difference in the concentration at PW-8. The concentration is approximately 13.7 μg/l (9.3 pCi/l) in groundwater pumped from PW-8 and 0.6 μg/l (0.4 pCi/l) from PW-9.

The effect of retardation on the plume at 20 years is more evident than that of dispersion (Figure 10-7). The retardation coefficient used for this simulation is approximately 7.4. With retardation, the concentration from PW-8 is only 0.14 μg/l (0.1 pCi/l) and no impact was observed in PW-9.

The effects of dispersion can be seen in plots of concentration versus time for PW-8 (Figure 10-8). This plot shows the variation in concentration with time at the pumping well with and without dispersion. It shows that in addition to increasing the value of the concentration, contamination reaches the production well sooner than the condition with no dispersion. The concentration at the well with retardation is small and does not show up at the scale of this plot.

10.7 Projected Future Conditions in the Quarry Environmental System

A major concern for the Quarry Residuals Operable Unit is whether potential future migration of uranium-contaminated groundwater could impact water quality at the St. Charles County well field. Although there will always be a level of uncertainty surrounding this question, the processes (redox reactions and dilution) that have prevented detectable uranium migration to the pumping wells are relatively robust. Dilution in the well field reduces the contribution of groundwater from sources north of the slough to less than 1% (Ref. 83). These processes are independent and provide redundant protection for the drinking water supply.

Quarry restoration, which may include backfilling, will likely decrease oxidation potentials downgradient from the quarry. These soils, which may be amended with organic material, will be saturated in the lower portions of the quarry. If amended with organic material, the soil will provide an environment where the free oxygen in groundwater will be consumed rapidly. The reduced groundwater will migrate downgradient into the bedrock and to the alluvium. Over time, influx of this groundwater should gradually reduce the oxidation potential of the alluvial aquifer north of the slough.

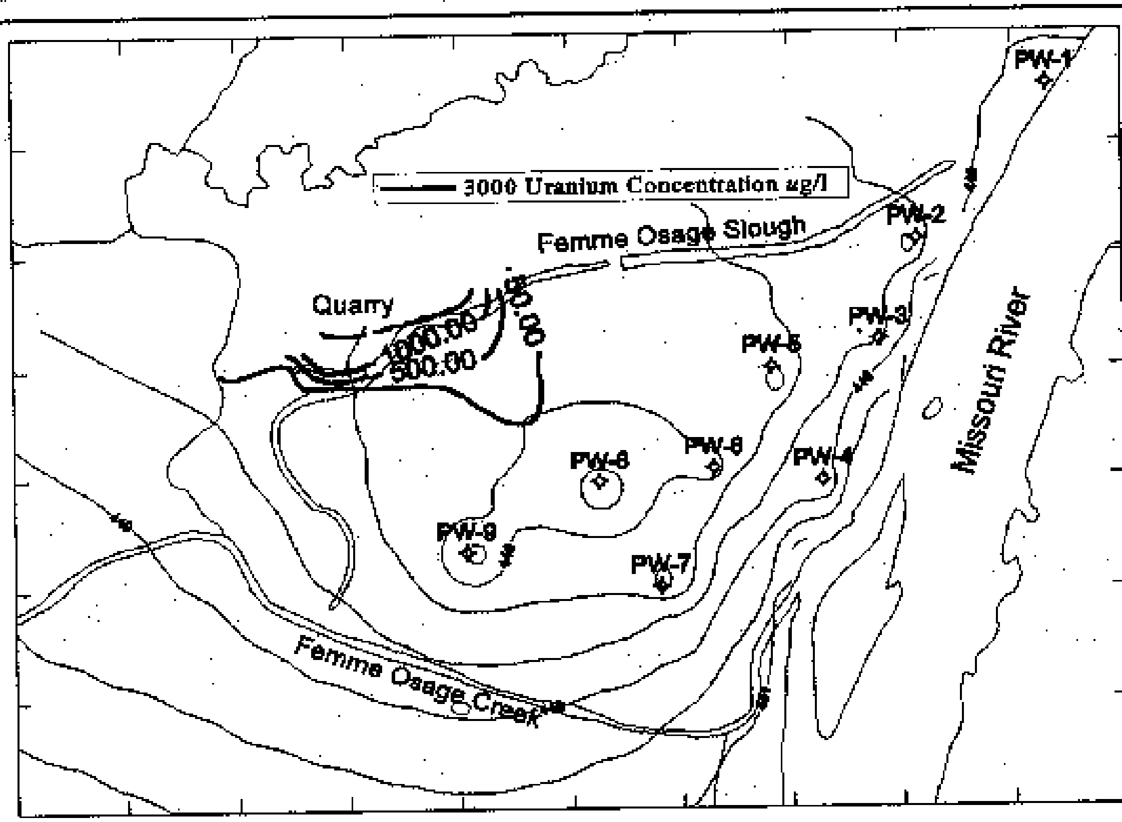

FIGURE 10-7 Uranium Isopleths for the Simulated Quarry Plume with Retardation

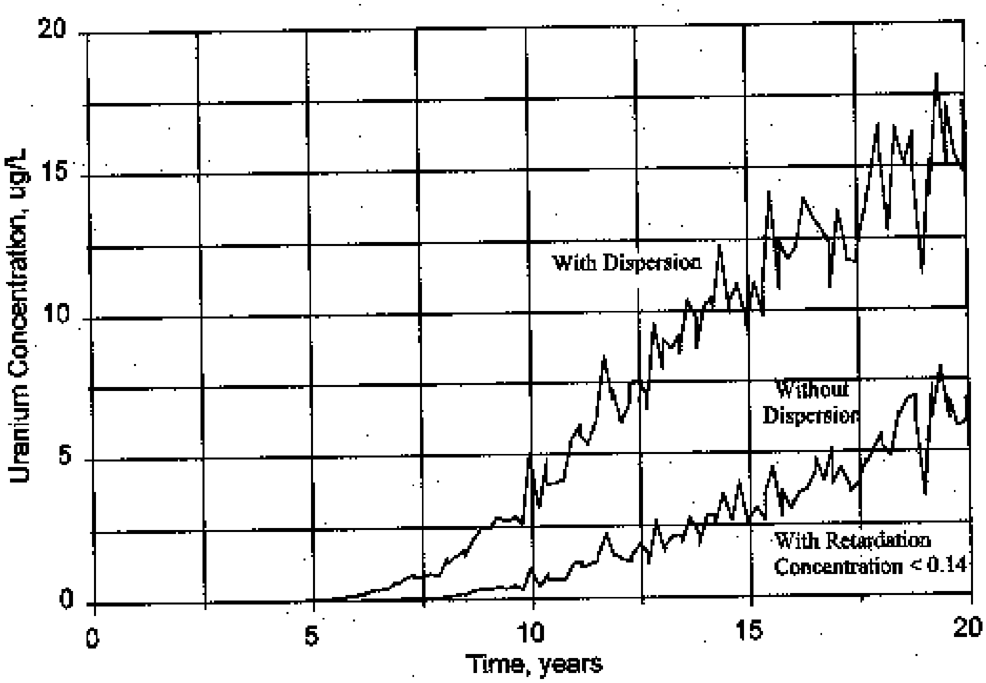

FIGURE 10-8 Simulated Change in Uranium Concentration in Production Well PW-8 with Time

Continued flushing at the alluvial aquifer north of the slough will gradually reduce uranium levels in groundwater. Although site-specific distribution coefficients have not been determined for the alluvial aquifer north of the slough, the values are expected to be high based on the presence of clay and organic material. Combined with the low hydraulic conductivity of the alluvium, an extended period of flushing may be required to desorb uranium in this portion of the aquifer.

Future redox potentials at shallow levels in the alluvial aquifer may vary with wet and dry climate cycles that change the elevation of the phreatic surface. Oxidation potentials should decrease during wet or flood periods and increase during dry periods as the saturated zone rises and falls, respectively. Extreme wet and dry periods have occurred during the last 10 years, but corresponding increases in contaminant mobility have not been observed. Future conditions may become more reducing if the area is allowed to remain flooded for long periods. It is unlikely that conditions would become more oxidizing than they were when the well field area was actively farmed. During farming, soils are regularly turned over, exposing new surfaces to the air; organic material is removed from the area during harvests; and potentially oxidized nutrients are applied to the soil.

11 SUMMARY OF BASELINE RISK ASSESSMENT

11.1 Significant Observations from the Baseline Risk Assessment

The radiological contaminants of potential concern (COPC) include uranium, Ra-226, Ra-228, and thorium (primarily Th-230). Chemical COPC include metals and nitroaromatic compounds. Polychlorinated biphenyls (PCBs) were also detected in the soils of the quarry proper. A list of COPC for the various areas is presented in the baseline risk assessment.

Consistent with current and likely future land use for the quarry area, potential exposure was evaluated for a recreational visitor at the quarry proper and Femme Osage Slough. The estimates for the slough should be representative of those for the creeks because contaminant concentrations reported for the creeks are generally lower than those reported for the slough. Exposure to groundwater at the quarry area is an incomplete pathway because areas with elevated contaminant concentrations are not used for residential, agricultural, or other purposes. In addition, the low yields determined for the area are not expected to support any sustained use for the shallow groundwater. However, in order to provide information concerning potential exposure from ingestion and dermal contact with contaminated groundwater, bounding calculations were performed for a hypothetical resident.

The results for the recreational visitor exposed to multiple locations and media via multiple pathways indicate that radiological and chemical risks are within the target risk range of 10^{6} to 10^{-4}. Hazard indices are also less than 1, indicating that systemic toxicity is not a concern. Upper-bound estimates of risk from exposure to groundwater by a hypothetical resident indicate several wells with a risk greater than 10^{4} located north of the slough and directly south and southeast of the quarry. The major contributors to risk are uranium and 2,6-DNT. Hazard quotients greater than 1 were also estimated for a few wells located in this area.

No risks were identified to aquatic biota for most contaminants of potential ecological concern. Current levels of aluminum, barium, manganese, and total uranium in the surface water of the Femme Osage Slough and the Little Femme Osage Creek have been identified as potentially posing risks to aquatic biota using these habitats. However, biotic surveys of the slough and creek found macroinvertebrate and fish communities typical of similar habitats in the Midwest, and no obvious adverse effects on aquatic biota were observed in the slough or creek.

Risk estimates for terrestrial wildlife based on modeling results indicated no risks to receptors foraging in the Femme Osage Slough or drinking from the slough or the Little Femme Osage Creek. Internal and external examinations of small mammals collected from the site failed to show any abnormalities that might indicate adverse effects on small mammals. Tissue analyses of fish indicated uranium concentrations within the range reported in the literature for contaminated and uncontaminated sites in North America and for which no adverse effects have been observed. Tissue concentrations of radionuclides in small mammals collected from the Quarry Residuals Operable Unit were comparable to levels detected in specimens from reference sites. On the basis of the absence of any observable adverse effects to aquatic or terrestrial biota, the generally low levels of potential risk identified for aquatic biota and no risks to terrestrial wildlife, the current levels of contamination in surface water and sediments from Femme Osage Slough and Little Femme Osage Creek do not appear to have impacted ecological resources at these habitats, and do not pose a future risk to biota at the site.

12 SUMMARY

12.1 General

- Any action that disturbs the archeological site on the south quarry rim will require Phase III mitigation.

- Contaminant discussions focus on naturally occurring parameters that exceed two times background and anthropogenic parameters greater than zero. Special emphasis is given to parameters that exceed water quality standards (groundwater and surface water) or screening criteria presented in the Work Plan (soil and sediment).

12.2 Air

- Rn-222, gamma radiation, radioactive airborne particulates, and asbestos are presently at background levels and are below U.S. Department of Energy (DOE) protection criteria.

- Rn-220 (thoron) exceeds background at one location on the northeast corner of the quarry proper.

12.3 Ecology

The ecological investigations indicate that there are no adverse impacts to biological communities in the vicinity of the quarry. This conclusion is based on the following:

- Survey data indicate no significant differences in species diversity and community equality between study areas and reference areas for trees and saplings/shrubs.

- The communities south of the quarry are typical of Missouri floodplain habitats.

- Studies of fish obtained from the Femme Osage Slough showed that biouptake of uranium was occurring, but levels did not pose a threat to human health.

- Benthic invertebrate diversity in Little Femme Osage Creek near the quarry did not significantly differ from the reference location upstream.

- Herpetofauna survey results indicate no significant differences between number and types of species observed at the quarry and the reference location.

- No State or Federal listed species were found during herpetofauna and vegetation surveys. Bald eagles were observed during winter surveys in the area between the quarry and the Missouri River.

12.4 Soils

- Limestone bedrock in the quarry proper does not exhibit fixed contamination.

- Soil in wall fractures within the quarry is relatively free of contamination.

- Isolated areas of contamination are present in the "triangle" area. Characterization in the triangle area will be performed when safe access can be established.

- Limited volumes of soil in quarry floor fractures and depressions and at the base of the sump are contaminated with radium, Th-230, and uranium. Other contaminants are present at low levels or were not detected.

- Low levels of uranium are sorbed onto soils located between the quarry and the slough. Low levels of other contaminants (radionuclides, nitroaromatic compounds, and metals) also occur in this area, primarily in the upper 5 ft interval. Transport to the area in the groundwater appears to be a plausible explanation for elevated uranium levels.

- Overbank flooding by the Missouri River may be a source of elevated metals in surface soils south of the quarry.

12.5 Surface Water and Sediments

- The quarry pond recharges gradually, primarily in response to precipitation, and the total uranium activity has been in the 400 pCi/l to 550 pCi/l range since pumpdown of the quarry pond in mid-April 1996.

- Surface water and sediments of the Little Femme Osage Creek have been influenced by activities at the former ordnance works.

- Many of the parameters elevated in the surface of the upper and lower Femme Osage slough are also elevated in the Missouri River which is routinely diverted to or floods the slough.

- Surface water and sediments in the Femme Osage slough have probably been impacted by migration of groundwater from the quarry containing elevated levels of uranium.

12.6 Hydrogeology

- The aquifer system at the quarry is composed of two media: limestone bedrock and alluvium.

- The bedrock units of interest in the quarry area are the Kimmswick Limestone, the Decorah Group, and the Plattin Limestone. Fractures in the Kimmswick Limestone extend downward into the Decorah Group which suggests that in the vicinity of the quarry, these units are hydraulically connected. The greatest number of vertical and horizontal fractures occur in the Kimmswick Limestone. The Plattin Limestone is massive with very little vertical or horizontal fracturing. The potential for groundwater movement in the limestone units is greater in the horizontal direction.

- Coarse-grained deposits comprise the bottom 20 to 80 ft of the Missouri River floodplain. Fine-grained deposits comprise the upper 15 to 25 ft of the Missouri River floodplain and the full thickness of the Little Femme Osage Creek and Femme Osage Creek alluvium. The fine-grained deposits consist of silty clay and clayey silt with alternating layers and lenses of fine sand and silts.

- Groundwater movement in the limestone units is predominantly controlled by the distribution of interconnected fractures. Preferential flow occurs along vertical fractures and horizontal bedding planes, most which occur in the Kimmswick Limestone. Where vertical fractures intersect bedding planes, the fractures are typically enlarged by dissolution.

- Groundwater movement in the alluvium is primarily dependent upon the grain size distribution of the sediments. Lower hydraulic conductivites are associated with fine-grained overbank deposits north of the slough. Higher hydraulic conductivities are associated with coarse-grained channel deposits south of the slough.

- Groundwater flows south and southeast in the limestone bedrock from the upland area to the alluvial floodplain.

- Groundwater flow in the coarse-grained alluvium beneath the floodplain is to the east towards the Missouri River.

- North of the slough, the hydraulic head within the alluvium generally decreases with depth, indicating downward movement of groundwater. Within the alluvium south of the slough, the hydraulic head also decreases with depth. Closer to the river, the hydraulic head within the alluvium is uniform or increases with depth, indicating the vertical component of movement is negligible, and the horizontal flow component is predominant.

- Interaction occurs between the slough and the alluvial aquifer. Typically, the surface water in the slough seeps into the groundwater. In localized areas, the groundwater discharges into the slough as indicated by hydraulic head measurements in the alluvium adjacent to the slough.

12.7 Groundwater Quality

- Uranium and nitroaromatic compounds are the primary quarry-derived contaminants in the quarry aquifers.

- Contaminant plumes are limited to the north side of the slough except for the presence of uranium at low levels in two monitoring wells (RMW2 and 1011) south of the slough.

- The significant reduction in groundwater contamination in the vicinity of the slough results from a geochemical reducing zone that degrades nitroaromatic compounds and precipitates uranium-bearing phases.

- Elevated arsenic levels along the slough are unrelated to the quarry.

- Concentrations of nitroaromatic compounds are decreasing in response to bulk waste removal and are expected to continue decreasing. Uranium concentrations have shown little decline, indicating that secondary sources are present in the aquifer, namely, soils contaminated with low levels of uranium (generally less than 30 pCi/g U-238).

12.8 Baseline Risk Assessment

- Radiological and chemical risks and the hazard indices are within the acceptable range for the recreational visitor at the quarry and Femme Osage Slough areas.

- The upper bound radiological and chemical carcinogenic risks and the hazard index for the recreational visitor ingesting groundwater are within acceptable risk ranges.

- No adverse effects to aquatic biota from quarry activities have been observed in the Femme Osage Slough or the Little Femme Osage Creek.

- The current levels of contamination in surface water and sediments from the Femme Osage Slough and the Little Femme Osage Creek apparently have not and will not pose a risk to ecological resources in these areas.

12.9 Additional Investigations

The results of this remedial investigation indicate that additional information would augment the understanding of the groundwater system and contaminant migration south of the quarry. The need to perform the following investigations to obtain this information will be evaluated:

- Determination of sorption/desorption coefficients of the alluvium with respect to uranium.

- Definition of the morphology of the fluvial deposits north and in the vicinity of the Femme Osage Slough.

12.9.1 Uranium Desorption Properties of the Alluvial Materials

Contaminated soils and aquifer materials are present in the alluvium north of the slough. The desorption rates of uranium from these materials has not been quantified, although estimates of acceptable ranges can be referenced. To fully evaluate natural flushing of the groundwater north of the slough, site-specific values need to be obtained to determine how long it will be before levels begin to significantly decrease.

12.9.2 Stratigraphic Control of Groundwater Movement in the Alluvium

The morphology of the fluvial deposits north of, and in, the vicinity of the Femme Osage Slough should be evaluated to better understand the distribution of contaminants and define potential pathways for contaminant migration to the south. Available soil and groundwater data indicate the vertical distribution of contaminants is complex but presently is not correlated to grain size or depositional features. The potential for contamination exists at well MW-RMW2, although no pathway to the south has been defined. Additional definition of the stratigraphy could be accomplished by performing borehole geophysical logs in existing wells or in new boreholes if drilling is undertaken.

13 REFERENCES

1. Argonne National Laboratory. *Work Plan for the Remedial Investigation/Feasibility Study-Environmental Assessment for the Quarry Residuals Operable Unit at the Weldon Spring Site*. DOE/OR/21548-243. Prepared for the U. S. Department of Energy, Weldon Spring Site Remedial Action Project by the Environmental Assessment Division. St. Charles, MO. January 1994.

2. MK-Ferguson Company and Jacobs Engineering Group. *Quarry Residuals Sampling Plan*, Rev. 1. DOE/OR/21548-382. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. January 1994.

3. MK-Ferguson Company and Jacobs Engineering Group. *Environmental Documentation Department Plan*, Rev. 0. DOE/OR/21548-359. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, St. Charles, MO. May 1994.

4. MK-Ferguson Company and Jacobs Engineering Group. *Remedial Investigations for Quarry Bulk Wastes*, Rev 1. DOE/OR/21548-066. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project. December 1989.

5. *Federal Register*, p 27620, July 22, 1987.

6. *Federal Register*, p 10516, March 13, 1989.

7. MacDonell, M.M., J.M. Peterson, and I.E. Joya. *Engineering Evaluation/Cost Analysis for the Proposed Management of Contaminated Water in the Weldon Spring Quarry*. DOE/OR/21548-039. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project. January 1989.

8. Argonne National Laboratory. *Record of Decision for the Management of the Bulk Wastes at the Weldon Spring Quarry*, Rev. 0. DOE/OR/21548-317. St. Charles, MO. September 1990.

9. U.S. Department of Energy. *Record of Decision for Remedial Action at the Chemical Plant Area of the Weldon Spring Site*. DOE/OR/21548-376. Oak Ridge Field Office. St. Charles, MO. September 1993.

10. U.S. Geological Survey. 7.5 Minute Series. Defiance Quadrant 1996.

11. MK-Ferguson Company and Jacobs Engineering Group. *Weldon Spring Quarry Construction Staging Area and Water Treatment Plant Site Remedial Action Characterization Report*, Rev. 0. DOE/OR/21548-200. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. September 1991.

12. Memorandum of Agreement Submitted to the Advisory Council on Historic Preservation Pursuant to 36 CFR 800.6(a). Submitted by U.S. Department of Energy, Oak Ridge Operations, Weldon Spring Site Remedial Action Project Office under cover of letter by Stephen H. McCracken, April 2, 1990.

13. St. Charles County Planning Department, Correspondence by FAX to Rheta Smith (PMC) from Lynn Hoban (St. Charles County). April 1996.

14. G.R. Walters. *Phase II Testing and Evaluation of Archaeological Site 23SC21, St. Charles County, Missouri*. Triad Research Services Cultural Resource Management Report No. 127. July 31, 1989.

15. U.S. Environmental Protection Agency. *RCRA Ground-Water Monitoring: Draft Technical Guidance*, EPA/530-R-93-001. Prepared by the Office of Solid Waste, Washington, D.C. November 1992.

16. National Oceanic and Atmospheric Administration. *1995 Local Climatological Data Annual Summary with Comparative Data, St. Louis Missouri (STL)*. ISSN 0198-2907

17. DOE Order 5400.5A, *Radiation Protection of the Public and the Environment*.

18. Pearson, Mark D. and Robert R. Spangler. "Calibration of Alpha-Track Monitors for Measurement of Thoron." *Health Physics*, Vol. 40, No. 5. May 1991.

19. Missouri Botanical Garden for East-West Gateway Coordinating Council. *An Introduction to the Biological Systems of the St. Louis Area*, Vol. 1. Prepared for St. Louis District Corps of Engineers. No date.

20. Information on species in the Weldon Spring Area was provided as an enclosure in a letter dated August 24, 1988, from D.F. Dickneite, Environmental Administrator, Missouri Department of Conservation, to Ihor Hlobowskyj, Argonne National Laboratory.

21. Haroun, L.A., J. M. Peterson, M.M. MacDonell, and I. Hlohowskyj. *Baseline Risk Evaluation for Exposure to Bulk Wastes at the Weldon Spring Quarry, Weldon Spring,*

Missouri. DOE/OR/21548-065. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. January 1990.

22. The information is in a printout from the Missouri Department of Conservation Heritage database as provided to Ihor Hlohowsky of Argonne National Laboratory under cover of a letter dated September 8, 1988, from Eleanor P. Gaines, MDC Data Manager.

23. Missouri Department of Conservation. *Rare and Endangered Species of Missouri Checklist*. Natural History Division. Jefferson City, MO. 1992.

24. MK-Ferguson Company and Jacobs Engineering Group. *Quarry Haul Road Ecological Survey*, Rev. 1. DOE/OR/21548-228. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. September 1992.

25. Environmental Laboratory. *Corps of Engineers Wetlands Delineation Manual*, Technical Report Y-87-1. Prepared for Department of the Army, U.S. Army Corps of Engineers. Vicksburg, Mississippi. January 1987.

26. U.S. Fish and Wildlife Service. *National Wetlands Inventory Map*. Scale 1:24,000. June 1989.

27. Lawrence Berkeley Laboratory. *Preliminary Draft: Radiological, Hydrogeological, Geochemical, and Geophysical Assessment of the Weldon Spring Quarry, Missouri Disposal Site*. LBID-152. University of California, Berkeley, CA. Work done under the auspices of the U.S. Department of Energy under Contract W-7405-ENG-48. January 1980.

28. Boerner, A.J. *Radiological Survey of the August A. Busch and Weldon Spring Wildlife Areas Weldon Spring Site, St. Charles County, Missouri*, Final Report. Prepared by Oak Ridge Associated Universities, for U.S. Department of Energy, Division of Remedial Action Projects. April 1986.

29. Marutzky, S.J., R. Colby, and L. S. Cahn. *Radiologic Characterization of the Weldon Spring, Missouri, Remedial Action Site*, DOE/ID/12548-22. Prepared for the U.S. Department of Energy, by United Nuclear Corporation Geotech. Grand Junction, CO. February 1988.

30. Berkeley Geosciences Associates. *Characterization and Assessment for the Weldon Spring Quarry Low-Level Radioactive Waste Storage Site*, DOE/OR-853; DE850005424. Prepared for U.S. Department of Energy, Oak Ridge Operations Office. September 1984.

31. MK-Ferguson Company and Jacobs Engineering Group. *Surface Soil Analytical Results for the Vicinity Property 9 Area*, Rev. 0. DOE/OR/21548-463. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. June 1994.

32. Roberts, Claude M. *Preliminary Investigation of Ground-Water Occurrences in the Weldon Spring Area, St. Charles County, Missouri*. Prepared for U.S. Department of the Interior. Indianapolis, Indiana. December 1951.

33. Richardson, R.M. *Possible Use of Quarry at Mallinckrodt Chemical Works, Weldon Spring, Missouri, for the Disposal of Uranium Contaminated Building Debris and Rubble, and Residues Containing Thorium and Uranium*. Prepared for U.S. Geological Survey. Oak Ridge, TN. June 1960.

34. Federal Insurance Administration. *Flood Insurance Rate Map, St. Charles County, Missouri*. Map Panel 2903150100B. U.S. Department of Housing and Urban Development, National Flood Insurance Program. Undated.

35. MK-Ferguson Company and Jacobs Engineering Group. *Annual Environmental Monitoring Report Weldon Spring, Missouri: Calendar Year 1987*. DOE/OR/21548-015. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, St. Charles, MO. 1988.

36. MK-Ferguson Company and Jacobs Engineering Group. *Annual Environmental Monitoring Report 1988*, Rev. 0. DOE/OR/21548-079. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, St. Charles, MO. June 1989.

37. MK-Ferguson Company and Jacobs Engineering Group. *Annual Site Environmental Report 1989*, Rev. 1. DOE/OR/21548-129. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project. St. Charles, MO. November 1990.

38. MK-Ferguson Company and Jacobs Engineering Group. *Annual Site Environmental Report for Calendar Year 1990*, Rev. 1. DOE/OR/21548-193. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. September 1991.

39. MK-Ferguson Company and Jacobs Engineering Group. *Weldon Spring Site Environmental Report for Calendar Year 1991*, Rev. 1. DOE/OR/21548-283. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project. St. Charles, MO. July 1992.

40. MK-Ferguson Company and Jacobs Engineering Group. *Weldon Spring Site Environmental Report for Calendar Year 1992*, Rev. 0. DOE/OR/21548-372. Prepared for the U.S. Department of Energy, Oak Ridge Field Office. St. Charles, MO. June 1993.

41. MK-Ferguson Company and Jacobs Engineering Group. *Weldon Spring Site Environmental Report for Calendar Year 1993*, Rev. 0. DOE/OR/21548-436. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. May 1994.

42. MK-Ferguson Company and Jacobs Engineering Group. *Weldon Spring Site Environmental Report for Calendar Year 1994*. Rev. 0. DOE/OR/21548-512. Prepared for the U. S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. May 1995.

43. Environmental Science and Engineering, Inc. *1994 Aquatic Surveillance Monitoring Program WP-402*, ESE Project No. 593-1109-0600. Final Report. Prepared for MK-Ferguson Company. St. Charles, MO. June 21, 1995.

44. Brugam, R.B., E. Danielson, C.T. Hubbard, and M. Malick. *Aquatic Biological Screening Investigation at the Weldon Spring Site*. Prepared by Department of Biological Sciences, Southern Illinois University. Edwardsville, IL. No date.

45. Environmental Science and Engineering, Inc. *1992 Aquatic Biological Monitoring - WP305*, ESE No. 592-1043-0400. Final Report. Prepared for MK-Ferguson Company. St. Charles, MO. April 1993.

46. Imes, J.L., and M.J. Kleeschulte. *Ground-Water Flow and Surface-Water/Ground-Water Interaction at Weldon Spring Quarry Disposal Site, St. Charles County, Missouri*. Water-Resources Investigations Report 96-4279. Prepared by the U.S. Geological Survey in cooperation with the U.S. Department of Energy. Rolla, MO.

47. Schumacher, J.G. *Geochemistry and Migration of Contaminants at the Weldon Spring Chemical Plant Site, St. Charles County, Missouri--1989-91*. U.S. Geological Survey, Open File Report 93-433, 102 pp.

48. Rockaway, John D., Ph.D. *Final Report Geomorphological Assessment, The Weldon Spring Site Remedial Action Project*, Subcontract No. 3589-SC-WP383. Prepared for the U.S. Department of Energy and MK-Ferguson Company. St. Charles, MO. May 10, 1993.

49. Kleeschulte, M.J. and L.F. Emmett. *Compilation and Preliminary Interpretation of Hydrologic Data for the Weldon Spring Radioactive Waste - Disposal Sites, St. Charles County, Missouri - A Progress Report*, Water Resources Investigations Report 85-4272. U.S. Geological Survey. Rolla, Missouri. 1986.

50. MK-Ferguson Company and Jacobs Engineering Group. *Remedial Investigations for Quarry Bulk Wastes*, Rev 1. DOE/OR/21548-066. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project. December 1989.

51. Whitfield, J.W., K. G. Brill, Jr., and W. J. Krummel. *Geologic Map of the Weldon Spring 7 1/2 " Quadrangle, St. Charles County, Missouri*. OFM-89-252-GI. Prepared for Missouri Department of Natural Resources, Division of Geology and Land Survey. Rolla, MO. 1989.

52. MK-Ferguson Company and Jacobs Engineering Group. *Alluvium Isopach and Bedrock Surface Maps Based on the Weldon Spring Quarry Area Surface Geophysical Surveys*, Rev. 0. DOE/OR/21548-464. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. May 1994.

53. Kleeschulte, Michael J. *Water-Quality Data for the Missouri River and Missouri River Alluvium Near Weldon Spring, St. Charles County, Missouri--1991-92*, U.S. Geological Survey, Open-File Report 93-109. Prepared in cooperation with the U.S. Department of Energy, Rolla, Missouri. 1993.

54. Layne-Western Company, Inc. *Groundwater Hydrology Investigation Weldon Spring, Missouri*, Vol. I. Hydrology Division. Kansas City, Kansas. January 8, 1986.

55. Bechtel National, Inc. *Hydrogeological Characterization Report for Weldon Spring Chemical Plant*, DOE/OR/20722-137. Prepared for U.S. Department of Energy, Oak Ridge Operations Office. Oak Ridge, TN. July 1987.

56. Bechtel National, Inc. *Weldon Spring Site Environmental Monitoring Report: Calendar Year 1983*, DOE/OR/20722-16. Prepared by Advanced Technology Division. June 1984.

57. MK-Ferguson Company and Jacobs Engineering Group. *Weldon Spring Quarry Supplementary Environmental Monitoring Investigations Sampling Plan*, Rev. 0. DOE/OR/21548-264. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, MO. August 1992.

58. Drever, James I. *The Geochemistry of Natural Waters*. Prentice Hall. Englewood Cliffs, NJ. 1988.

59. Schumacher, J.G., C. E. Lindley, and F. S. Anderson. *Migration of Nitroaromatic Compounds in Unsaturated Soil at the Abandoned Weldon Spring Ordnance Works, St. Charles County, Missouri*. No date.

60. Hem, John D. *Study and Interpretation of the Chemical Characteristics of Natural Water*, 3rd ed. U.S. Geological Survey Water-Supply Paper 2254. No date.

61. Brookins, Douglas G. *Eh-pH Diagrams for Geochemistry*. Springer-Verlag. New York. No date.

62. Dzombak, D.A. and F.M.M. Morel. *Surface Complexation Modeling*. John Wiley and Sons. New York. 1990.

63. Korte, N. "Naturally Occurring Arsenic in Groundwaters of the Midwestern United States." *Environ Geol Water Sci*. Vol 18, No. 2, pp. 137-141

64. U.S. Environmental and Protection Agency. *USEPA Contract Laboratory Program National Functional Guidelines for Inorganic Data Review*. 9240.1-05-01, PB 94-963502, EPA 540/R-94/013. Prepared by the Office of Emergency and Remedial Response. February 1994.

65. U.S. Geological Survey Professional Paper 1270. *Element Concentrations in Soils and Other Surficial Materials of the Conterminous United States*.

66. MK-Ferguson Company and Jacobs Engineering Group. *Radiological and Chemical Uptake in Game Species at the Weldon Spring Site*. DOE/OR/21548-426. Prepared for the U.S. Department of Energy, Weldon Spring Site Remedial Action Project. Weldon Spring, Missouri. July 1995.

67. Bolt, G.H. and M.G.M. Bruggenwert. *Soil Chemistry A. Basic Elements*. Elsevier Scientific Publishing Company, 1976.

68. Dunbabin, J.S. and K.H. Bowmer. *Potential Use of Constructed Wetlands for Treatment of Industrial Wastewaters Containing Metals*. The Science of the Total Environment, Vol. 111 (1992) pp. 151-168.

69. American Public Health Association. *Standard Methods for the Examination of Water and Wastewater*, 19th Ed. Washington, D.C. American Public Health Association, 1955.

70. Huey, E.A. *Report of Preliminary Geological, Hydrological, and Radiological Survey at the Weldon Spring Quarry During 1976 and 1977*. National Lead Company of Ohio. December 14, 1978.

71. Kleeschulte, M.J. and L.F. Emmett. *Hydrology and Water Quality at the Weldon Spring Radioactive Waste Disposal Sites, St. Charles County, Missouri*. U.S. Geological Survey Water Resources Investigations Report 87-4169. Rolla, MO. 1987.

72. Bechtel National, Inc. *Weldon Spring Site Environmental Monitoring Report - Calendar Year 1984*. DOE/OR/20722-58. Prepared for U.S. Department of Energy, Oak Ridge Operations Office. July 1985.

73. Bechtel National, Inc. *Weldon Spring Site (WSS) Environmental Monitoring Report: Calendar Year 1981*. Prepared for the U.S. Department of Energy. Oak Ridge, TN. May 1983.

74. MK-Ferguson Company. *Water Quality Phase I Assessment Report*. Rev. 0. DOE/OR/21548-003. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, Missouri. December 1987.

75. Fishel, V.C. and C.C. Williams. *The Contamination of Ground and Surface Waters by Liquid Wastes from the Weldon Spring Ordnance Works, Missouri*. Prepared for U.S. Department of the Interior. Lawrence, KS. January 1944.

76. Weidner, R.B. and M.W. Boback. *Weldon Spring Storage Site Environmental Monitoring Report for 1979 and 1980*. Prepared for the U.S. Department of Energy, Weapons Division of Oak Ridge Operations, by Feed Materials Production Center, NLO, Inc. Cincinnati, Ohio. April 19, 1982.

77. Mallinckrodt Chemical Works. *AEC Quarry Environmental Report*. Prepared for the Atomic Energy Commission by the Uranium Division. Contract No. W-14-108-Eng-8. This is a series of reports, first quarterly, then beginning in 1962 semiannual. Issues consulted were 4th Quarter 1960; 2nd, 3rd, and 4th Quarter 1961; 1st and 2nd Semiannual 1962; 1st Semiannual 1963; and 1st Semiannual 1964.

78. Kaye, M.E. and J.L. Davis. *Chemical Characterization Report for the Weldon Spring Quarry St. Charles County, Missouri* (Draft). DOE/OR/20722-176. Bechtel Job No.

14501. Prepared for the U.S. Department of Energy Oak Ridge Operations Office by Bechtel National, Inc. Oak Ridge, TN. June 1987.

79. Lenhard, L.A., J.N. Holt, and F.H. Belcher. *Weldon Spring Raffinate Pits and Quarry Task Force Report*. WSRAP Technical Library Reference Sequence No. RP-2. June 1, 1967.

80. MK-Ferguson Company and Jacobs Engineering Group. *Remedial Investigation for the Chemical Plant Area of the Weldon Spring Site*, Vol. 1. DOE/OR/21548-074. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project. November 1992.

81. Darcy, H. *Les fontaines publiques de la ville de Dijon*, V. Dalmont, Paris, 647 pp, 1856.

82. Langmuir, D. *Uranium Solution-Mineral Equilibria at Low Temperatures with Applications to Sedimentary Ore Deposits*. Geochimica et Cosmochimica Acta. Vol. 42. 1978.

83. MK-Ferguson Company. *WSSRAP Quarry Residuals Remedial Investigation Dilution Calculations*. Rev. 1. Technical Memorandum No. 3840TM-3027-01. Prepared for the U.S. Department of Energy, Oak Ridge Operations Office. St. Charles, Missouri. April 1997.

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MK-Ferguson Company
Weldon Spring Site Remedial Action Project

TRANSMITTAL OF CONTRACT DELIVERABLE

Date: 28 Jul 97 **Transmittal No.:** CD-0132-01

Title of Document: Remedial Investigation for the Quarry Residuals Operable Unit of the Weldon Spring Site, Weldon Spring, Missouri

Doc. Num.: 587 **Rev. No.**: 1 **Date of Document**: July 1997

Purpose of Transmittal: Request for Department of Energy acceptance of contract deliverable.

In compliance with the Project Management Contract, MK-Ferguson Company hereby delivers the attached document to the U.S. Department of Energy, Weldon Spring Site Office. The document has been reviewed and approved by Project Management Contractor management.

The document will be considered accepted unless we receive written notification to the contrary within 30 days of the date of this transmittal.

Number of copies transmitted: 12

James R. Powers

James R. Powers
Project Director

TMP: Form Contract Deliverable